

P.A.W.S.

Protected **A**ccess for **W**hiskered **S**ubjects: AI-Assisted Litter Box System



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Chapter 1 - Executive Summary

Our senior design project is looking at a problem that many homes with both cats and dogs face: How can you keep a dog out of a cat's litter box? Litter boxes attract dogs, the smell alone is enough to tempt a curious dog, and if the dog gets in, it can make a big mess. Our combination of AI recognition technology, infrared sensors, and a motorized door makes a safe access system that lets only the cat use the litter box.

At the heart of our design is an infrared camera and sensor system. We've placed these strategically to make them very effective for our purposes. If anything comes within a certain range of the litter box, we want to know about it. We use recognition algorithms for the task of distinguishing cat versus dog. The design's goal is to ensure that only cats trigger the motorized door to open, once the system has confirmed it is in fact a cat in front of the litter box. Otherwise, the system will keep the door closed if a dog has been detected.

We decided to use IR sensors and an AI-based recognition system for a reason. We wanted an inexpensive way to create a reliable and efficient device. The IR camera brings the reliable part to the table; it can detect in low-light conditions. This is vital for an application in the home, where light conditions can swing dramatically from one moment to another. The efficient side of our system can be chalked up to the AI object-recognition component, which improves the accuracy of the system, which can reduce false triggers causing the door to open for the wrong pet.

For pet owners, the design has several upsides. It keeps dogs out of the litter box, which naturally leads to increased hygiene. More to the point, though, it makes sure dogs don't eat litter and, in so doing, protects them from consuming harmful chemicals often found in litter. All that said, we are especially interested in how well the system achieves the main point of a litter box: giving the cat a space that is safe, private, and secure.

Overall, our litter box system with assisted AI represents a practical and effective option for pet owners in households with multiple types of pets. The smart detection, the precise access control, and the user-friendly automation of the device all contribute to the enhanced convenience and cleanliness of the option it offers, and its very existence serves as a potential lifesaver for the types of pets it serves.

Chapter 2 - Project Description

This chapter provides a comprehensive overview of the project, providing an overview of all foundational elements. It delves into the project's background, motivations, goals and objectives, before continuing with market assessment of comparable existing products. Next, the chapter outlines the detailed engineering requirements and specifications, presenting prototype illustrations that capture both the initial concept and final design iterations. It also examines the mobile application's architectural design, elaborating on the project's functional dynamics, and includes comprehensive hardware and software diagrams that show the project's technical and logical mechanisms.

2.1 Project Background and Motivation

Allowing dogs constant access to a litter box can be the origin of some serious health risks, both for the dog and for humans within the same household. Litter boxes are designed for cats, and their waste should be handled in a particular way. When dogs have free roam to a litter box, they might engage in a behavior called coprophagia, which is when they ingest feces[1]. According to PetMD, this is a very common practice among canines[2]. However, this behavior can lead to exposure to a great deal of harmful bacteria and parasites. This will lead to many gastrointestinal issues, and in severe cases it can lead to deadly infections.

Toxoplasma gondii is a parasite commonly found in cats, and is transmitted through their feces, however it can be found in most warm-blooded animals. This parasite causes an infection called toxoplasmosis. Although it is not deadly to an average adult, it can be very dangerous to pregnant women and immunocompromised people. Toxoplasmosis can even lead to birth defects and even miscarriage[3].

When dogs continuously engage in this behavior, not only is it dangerous for the humans in the same household, but it can also be dangerous to their health. Most types of litter are designed to clump when in contact with the cat's urine and feces, for the ease of clean up, this clumping factor can cause gastrointestinal blockages on the dog if they carry on eating litter. This will lead to severe stomach issues causing constant veterinary visits[4]. Another issue that can affect dogs is the dust from the litter, which may affect their respiratory system. Furthermore, dog's hygiene habits vastly differ from cats, it's not part of their behavior to clean themselves thoroughly like cats. Their lack of hygiene will increase the spread of litter and fecal matter throughout a household.

2.2 Goals

This section will cover the goals set to be pursued throughout the journey of the P.A.W.S project. Overall, the main goal is to provide a cat-only accessible litter box, but to accomplish this there are a subset of goals we have come up with that will build up to that fulfillment. First are the basic goals, which we expect to accomplish entirely that make up the core system and operation of the P.A.W.S litter box to essentially function correctly. Second, we have advanced goals we would also like to include which are not exactly necessary but will enhance the features of P.A.W.S. litter box that can improve reliability and user experience. Lastly, the advance goals we have set are not required but also improve specific elements of our system if time allows and implementation is feasible.

2.2.1 Basic Goals

Our basic goals are what we expect to achieve throughout the development of P.A.W.S. Below is a list of our basic goals we set to accomplish for the initial functionality of the system:

- Enclosure that houses a litter box.
- A top-mounted hinged door.
- Motorized plexiglass door.
- Ensure that the door does not close while a cat is entering, exiting, or in the doorway.
- Direct Access for the user.

Initially, the design involves creating a litter box housed by a wooden enclosure that can seamlessly blend into everyday furniture. There will be infrared proximity sensors that will initially detect when the cat is within a foot of the enclosure. There will be a cat recognition verification system implemented to allow exclusive access for the cat, which will trigger the motorized plexiglass door that will provide entry and exit for the cat only, along with infrared safety sensors to prevent the door from closing while the cat is in the doorway, preventing possible injury.

Other features will include a top-mounted hinged door, allowing easy access for placing, removing, or cleaning the litter box. Also, for added security, a manual override switch will allow the owner to open the door for direct access in case of power or mechanical failure.

2.2.2 Advanced Goals

The advanced goals are some of the core elements that will set P.A.W.S apart from other ordinary litter boxes. Below is a list of the advance goals that will enhance our system:

- AI object detection.
- Live feedback to the user.
- User friendly.

The design features AI-powered object detection through real-time image processing, allowing the system to identify whether a cat, dog, or neither is in front of the enclosure. This is the type of verification system mentioned from the basic goals we will implement and focus on because we do not want to have any false positive access to the litter box.

Also, we want to include a mounted LCD screen on top of the enclosure that will display an emoting character, with expressions that change based on movement detection and pet identification.

Ideally, we will integrate a mobile app that will let users monitor a live camera feed to track door opening times when a pet triggers the door. The system will notify the owner of litter box activity via a notification. This cross-platform app will also enable the user to adjust settings for the enclosure, LCD screen, and motorized door. This type of customization will allow the cat owner to manage their household with ease.

2.2.3 Stretch Goals

The stretch goals will help enhance elements of our systems functionality if we have the time to implement and are feasible enough to include. Below is a list of the stretch goals we will look to include if possible:

- Allow the owner to save snapshots locally.
- Distinguish pet usage.
- Integrated weight tracking.
- Enhanced privacy for the pet.

Furthermore, we have stretch goals we want to include that aren't required for the main functionality of our system but will be additional benefits to the user if they can be added. This includes allowing the owner to save snapshots from the live camera feed locally. If they have multiple cats, it would be useful to allow them to categorize images by pet.

Other stretch goals include a cat paw-pad scanner that will identify and note multiple pets' litter box usage. We may also want to integrate data collection such as weight tracking to better determine pet health over a long period of time, which can help the owner avoid costly medical bills for their pet.

Lastly, we would add an improvement with a liquid crystal sheet (turns opaque when voltage applied) attached to the plexiglass door to provide privacy to the cat once it enters the enclosure.

2.3 Objectives

The primary objectives of the P.A.W.S. smart litter box system is using technological innovation to create a protected and private space for the bathroom needs of felines, keep canines from rooting in the cat litter, and to overall promote a clean home environment. By preventing unauthorized access, particularly from canines who regularly engage in ingesting feces, the system aims to minimize the spread of harmful bacteria while safeguarding them from ingesting potentially hazardous substances. Additionally, the system can be developed to monitor and track cats' bathroom patterns, enabling early detection of potential health issues (e.g., by identifying sudden changes such as increased frequency of visits or extended duration per use). Ultimately, the P.A.W.S. project solution seeks to enhance a sanitary living environment for all household members.

2.3.1 Objectives for Basic Goals

Initially, the objectives for our basic goals will specifically relay how we accomplish those goals. A list of our objectives for basic goals is given below:

- A 2 x 1 x 2 foot wooden enclosure frame.
- Infrared proximity sensors.
- Stepper Motor
- Safety Sensors
- Manual override switch.

The objectives for our basic goals of the system will feature a durable wooden enclosure that integrates seamlessly into household furniture. It will include infrared proximity sensors calibrated to detect the cat's presence within a set distance, even in varying lighting conditions. A motorized plexiglass door with stepping motors and safety sensors will ensure safe entry and exit, only closing when the cat has fully exited. For added convenience, the system will have a top-mounted hinged door with hydraulic hinges for easy access, along with a manual override switch connected to the Raspberry Pi for security in case of system failure.

2.3.2 Objectives for Advanced Goals

Next, the objectives for our advanced goals will help further develop our system as well to distance our project from other similar products. Below is a list of the objectives for our advanced goals:

- AI object detection processing algorithm.
- LCD screen that displays an emoting face/character reacting to the environment.
- Mobile App integration.
- Live camera.

The objectives for our advanced goals include developing and implementing AI-powered object detection that ensures exclusive access for the recognized cat by minimizing false positives and preventing unauthorized entry by other pets. Additionally, the system will feature a mounted LCD screen that displays an animated character with five dynamic expressions that respond to motion and pet identification within 1 second. A cross-platform mobile app will be developed, offering a live camera feed, door activity tracking, and push notifications, along with customizable settings for key features.

2.3.3 Objectives for Stretch Goals

Furthermore, the objectives for our stretch goals include several innovative features to enhance user experience and pet monitoring. Listed below is our objectives for the stretch goals:

- MicroSD Card to save snapshots.
- A cat paw-pad scanner.

- Weight scale integration.
- Liquid crystal sheet attached to plexiglass door.

The mobile app will be developed to allow users to save high-resolution snapshots from the live camera feed to their local devices, with seamless download capability and the ability to organize images by pet. Additionally, a cat paw-pad scanner will be integrated into the enclosure to accurately recognize individual pets and link to the data collection module, enabling users to log and review litter box usage in the app. The system will also incorporate a weight tracking feature within the litter box, displaying weight trends and providing alerts for significant changes, with comprehensive testing. Finally, we'll implement a liquid crystal sheet mounted on the plexiglass door that turns opaque for cat privacy using a relay switching mechanism.

2.4 Existing Products

This subsection discusses existing products related to the project, analyzing the similarities, differences, and core functionalities between the two.

2.4.1 Market Analysis

Two prominent players in the smart pet-care field are SureFeed and Meowspace, each providing unique solutions to common multi-pet household challenges. SureFeed specializes in Microchip Feeders, which grant food access only to pets with correct identification microchips or SureFlap RFID collar tags. This technology proves particularly useful in scenarios where a pet requires prescription food, there are greedy pets present that will attempt to steal their companions' meals, and where a pet's weight needs careful management. Meowspace, on the other hand, offers a selective-access pet enclosure that doubles as both a food and litter-box protection system. It features a locking pet door that can be unlocked via magnetic collars, RFID-tag embedded collars, or embedded microchips.

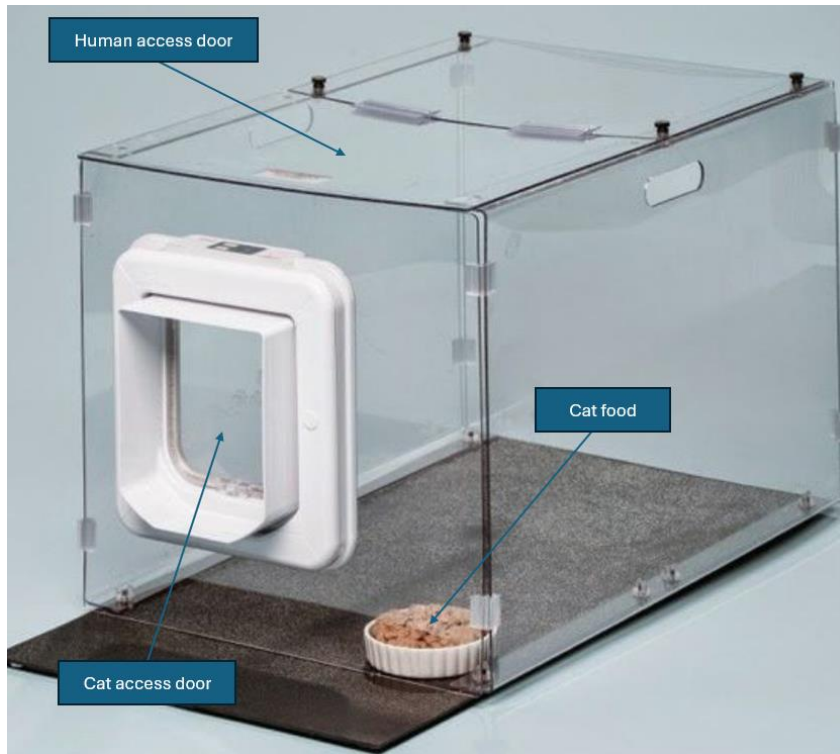


Figure (2.1) - MeowSpace Regular Sized Microchip System.

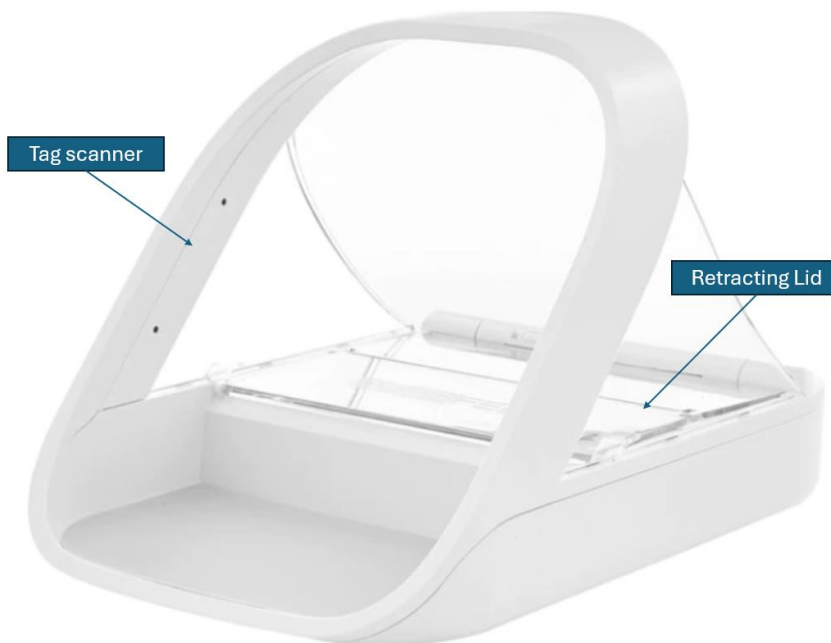


Figure (2.2) - SureFeed Microchip Small Dog & Cat Feeder.

While these systems offer innovative solutions, they share a common limitation: reliance on external hardware attached to the animal. This dependency, whether through embedded microchips or collars, presents several potential issues, such

as damage risk during rough play or outdoor adventures, discomfort for cats unaccustomed to wearing collars, potential hazards unless quick-release functions are incorporated, expense of multiple collars for multi-cat households, and inconvenience for cat-fostering homes or frequent pet-sitters who would need to regularly update device information.

Despite these advanced options, the market still lacks a fully cohesive, dog-excluding cat litter protection system. The P.A.W.S. provides a more comprehensive solution, featuring universal cat recognition with an IR imaging software without relying on collars or microchips and making it unaffected by light conditions. It also enables effective dog exclusion, and the app control allows for monitoring pet usage and aiding maintenance. P.A.W.S. provides a more accessible, hardware-hassle free, and user-friendly solution for all types of cat owners, from single-cat households to fostering environments, to felines with and without microchips and special collars.

2.5 Engineering Requirements and Specifications

This subsection discusses the engineering requirements and specifications of the project. Further details on each requirement or component can be found in Chapter 3.

2.5.1 Specifications

In this subsection, both the engineering requirements for the prototype as well as the individual components comprising the prototype are discussed. These specifications were developed and obtained by running the market analysis and examining similar products.

Table (2.1) - Engineering requirements specifications for the performance and physical features of the envisioned system. The demonstrable specifications are highlighted.

Product Requirement	Requirement Specification
The system shall use a proximity sensor to detect objects within a certain distance of the enclosure	≤ 1.5 feet
The system shall use an IR imaging camera with at least 90% identification accuracy	≥ 90 %
The system shall have a field of view for the IR imaging camera of at least 75°.	≥ 75 °
The system shall have a response time from the Raspberry Pi of 5 seconds or less.	≤ 5 seconds
The motorized rail-system shall move at a speed of at least 1 cm/sec.	≥ 1 cm/sec
The system's fully enclosed structure shall have minimum dimensions of 3' x 2' x 2'.	$\geq 3' \times 2' \times 2'$ feet

The system's plexiglass door shall have a maximum dimension of 16" x 16".	$\leq 10" \times 10"$ inches
The LCD display shall have brightness between 300 and 600 nits.	300-600 nits
The IR proximity sensor shall have an angle range of 45°-60°.	45-60 °
The IR proximity sensor light wavelength shall be approximately 940 nm.	~940 nm
The Velostat shall detect a minimum pressure of 1 lb.	≥ 1 lbs

Table (2.2) - Engineering specifications for individual key components/subsystems.

Component(s)	Parameters	Specification
IR Imaging camera	Identification Accuracy	$\geq 75\%$
	Field of view	≥ 75 degrees
Raspberry Pi	Response Time	Within 5 seconds
Motorized rail-system	Speed	Minimum 1cm/sec
Fully-enclosed rectangular structure	Dimensions	Minimum 3' x 2' x 2'
Plexiglass door	Dimensions	Maximum 10" x 10"
LCD display	Brightness	Ranging from 300-600 nits
IR proximity sensor	Field of View	45-60°
	Wavelength	940 nm
IR break-beam sensor	Range	12 in
	Field of View	$< 10^\circ$
Velostat	Pressure	1lb minimum

2.6 Prototype Illustrations

This subsection presents the evolution of the design process, from initial conceptualization to final implementation. The team's prototype illustrations for both the physical hardware enclosure and the integrated mobile application interface are included as well as progressive renderings demonstrating the refinement of the project design.

2.6.1 P.A.W.S. Enclosure Design

The following presents the initial design concepts and 3D prototype models of the enclosure, as well as a detailed state-sequence diagram of the enclosure. The initial design components of the main structure included a box-shaped enclosure with a painted exterior, two human-access doors, a dedicated cat entrance door, an LCD display, a camera module, and an IR detection system using an IR flood light and IR receiver module (refer to figure 2.3). The IR flood light would be used to illuminate the area and the IR receiver module would detect the reflected light. This system would have required more power and complexity due to the flood light component. In our revised IR detection system, the flood light is replaced with a simpler IR proximity sensor with a detection range of 1 foot from the door. It's more energy-efficient and reliable for obstacle detection while simplifying the overall system design.

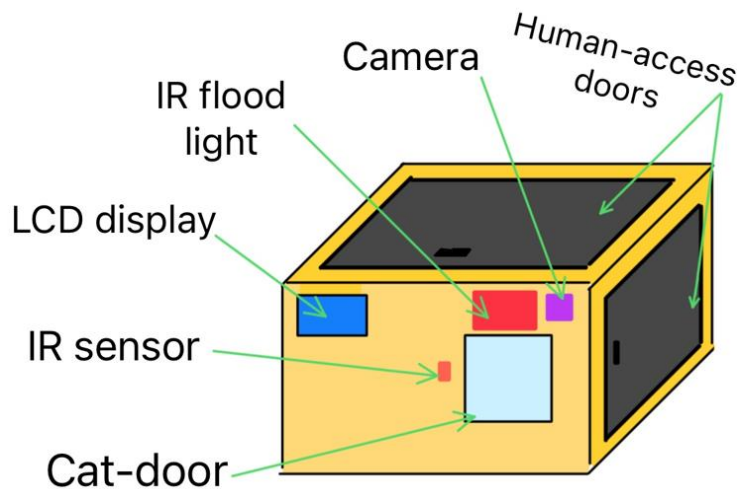


Figure (2.3) - Initial design concept for the physical P.A.W.S. litter box structure.

Additionally, the P.A.W.S. enclosure underwent significant dimensional refinement throughout its development process. The initial specifications called for a generously sized structure measuring 2 feet in width, 3 feet in length, and 2 feet in height. These original dimensions were deliberately chosen to be spacious, ensuring ample room for all potential component configurations and providing sufficient working space during the development phase. However, as the project progressed through multiple iterations, several key factors led to its strategic downsizing. After constructing and testing the plexiglass door's linear rail system as well as taking measurements of all major components, the team gained valuable insights into the actual space requirements needed for sufficient mechanical clearance, which revealed opportunities for space optimization.

While the reduced dimensions do limit the number of configurations possible for the layout of the components, the benefits of a more compact design outweighed these concerns. The decision to scale down was ultimately driven by practicality. A smaller physical footprint enhances user convenience, reduces material costs for construction, and improves overall portability and placement in typical home environments. Most importantly, this size optimization is achieved without compromising the core functionality of the system.

2.6.2 P.A.W.S. Enclosure Key States and Interactions

The intelligent access control system for the cat litter box enclosure can be broken down and illustrated by five key states and their interactions. This is diagrammed and explained further in both Figure 2.4 and Table 2.3 below.

The system demonstrates several smart design features, with power efficiency via the idle state, multiple safety checks for ensuring pet safety, redundant sensors for reliable operation, automated timing system for door opening and closing, and clear state transitions based on the numerous sensor inputs.

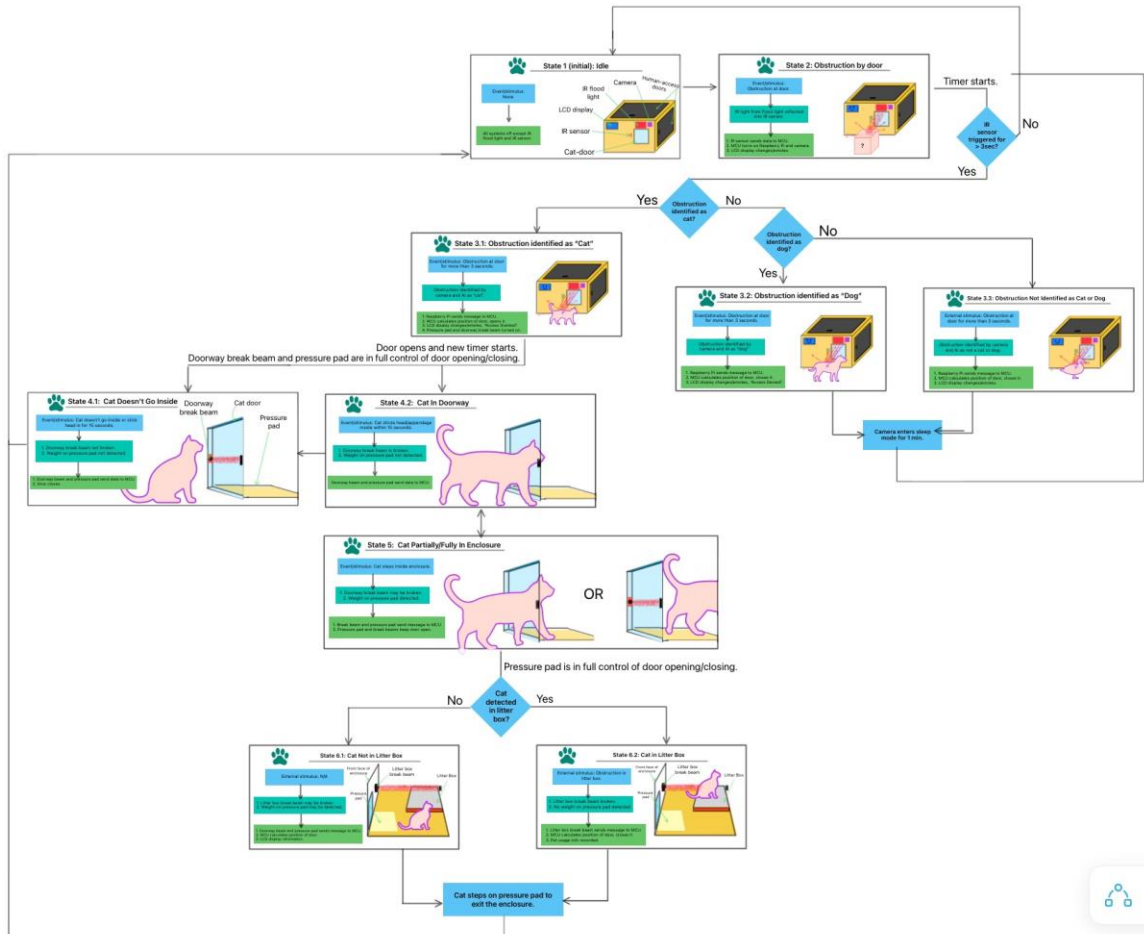


Figure (2.4) - Initial sequence of P.A.W.S. states, detailing the functionality and access into the enclosure from start to finish.

Table (2.3) - The envisioned physical system's states broken down into five key states and their interactions and/or interactions.

Key States	Interactions/Transitions
1. Initial State (Idle)	- System is in low power mode - Only IR proximity sensor is actively monitoring - Waits for objects within 1 foot of door

2. Detection & Identification	• IR sensor triggers camera module • Computer vision system identifies object • Decision making: ◦ If cat: proceeds to door opening ◦ If non-cat: returns to idle state
3. Safety Mechanisms	• Multiple redundant sensors ensure safe operation: ◦ IR break beam in doorway ◦ Pressure pad inside enclosure ◦ Timer system for automated closing • Any sensor activation keeps door open • Timer resets when sensors are triggered
4. Entry Sequence	• Door opens upon cat identification • Stays open while: ◦ Break beam is interrupted

	○ Pressure pad is activated ○ Timer hasn't expired
5. Exit Sequence	● Similar to entry but reversed ● Pressure pad activation triggers door opening ● Door remains open until cat completely exits ● Returns to idle state after successful exit

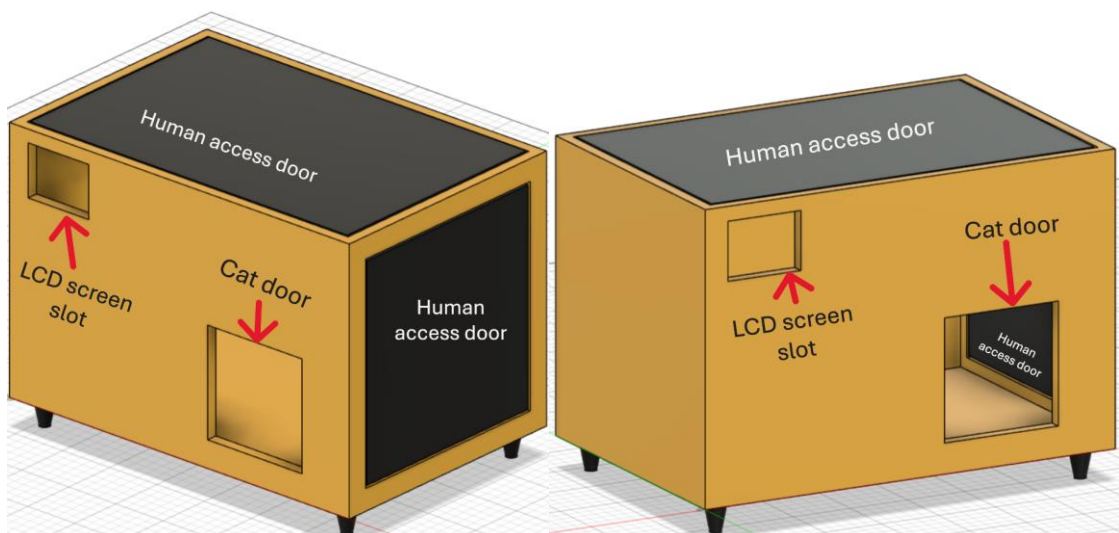
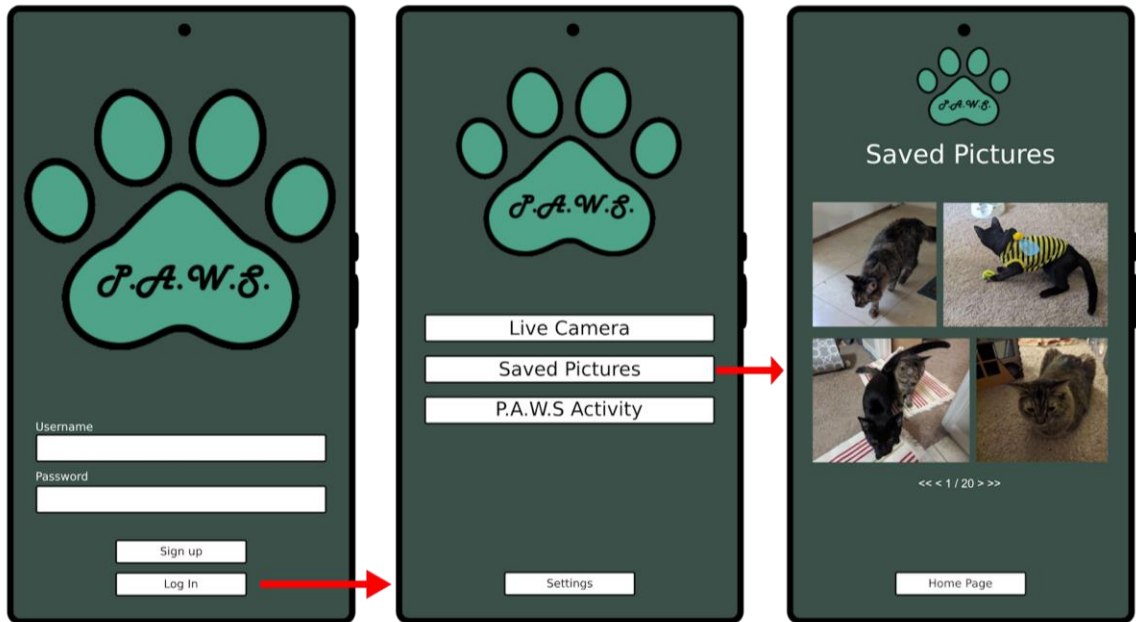


Figure (2.5) - Initial 3D prototype concept for the physical P.A.W.S. litter box enclosure

2.6.3 Mobile Application Design

The following presents the initial design mockup of the mobile app.

Figure (2.6) - Design mockup of the integrated mobile app. Examples include the sign-up/sign-in page, the home screen, and the “Saved Pictures” tab.



2.7 Functionality of Design

This subsection discusses the project's dual architecture, addressing both the operational dynamics of the enclosure as well as the integrated mobile application.

2.7.1 P.A.W.S. Enclosure Functionality

The enclosure will have a fully-enclosed, hollow rectangular form factor made from wood (refer to Figures 2.3-2.5). Its dimensions will be 3 feet in length by 2 feet in width by 2 feet in height. There will be a human-access door on the top face of the structure to allow for easy cleaning and maintenance. This access door will feature hydraulic hinges to stay in place when the user opens it. A motorized linear rail system will be attached to the front face of the structure and will serve as the actuator for sliding the plexiglass door, effectively opening and closing the 16-by-16 inch opening in the lower right corner of the front face of the structure). An LCD screen will be secured into the structure at the top left corner of the front face. Four 2.5-inch long tapered legs are attached to the underside of the enclosure. The structure will be fully painted with the P.A.W.S. logo featured on

the top face of the structure, and the authors plan to color-match the final logo design as well.

2.7.2 Mobile Application Functionality

The P.A.W.S. project will have an integrated mobile application. Upon first-time startup, a user is prompted to either log in with a previously created account, or sign up to create a new account. A P.A.W.S. enclosure can be connected to the account, and all corresponding functions will be available to the owner. These functions currently include:

- Receiving notifications when there is important activity detected by the sensors and/or the camera.
- Accessing a live video feed from the front-facing camera.
- Saving and viewing snapshots taken by the camera when a pet is detected nearby the P.A.W.S. enclosure.
- Viewing historical data of when the door is triggered to open. This data is especially useful for monitoring pet health over a long period of time.
- Access/modify enclosure's settings, LCD screen, and motorized door.

The mobile app will communicate with the P.A.W.S. enclosure through the Raspberry Pi's integrated WIFI capability. If not currently being interacted with, the Pi should stay in low-power mode in order to minimize power consumption, and thus lower active temperature. Saved pictures and activity logs are stored locally on the user's phone, and the live video is streamed directly from the Raspberry Pi only when being actively viewed. Additionally, the user will be able to directly activate the motor regardless of current detection status. Allowing manual control is a highly important safety feature should any electrical or mechanical failure take place.

2.8 Hardware Block Diagram

The hardware of the P.A.W.S. project can be split into five primary systems: the main PCB system, the Pi system, the optics system, the rail system, and the power system. Below is an overview of each system, its components, and its interdependencies.

2.8.1 The Main PCB System

At the core of the project lies the main PCB system, which serves as the central control hub. This system is comprised of three key components: the microcontroller (MCU), a motor driver, and a pressure pad. The MCU is responsible for coordinating communication and control across the entire hardware architecture. The motor driver plugs into the main PCB and provides the necessary interface from the MCU to the motor within the rail system. Meanwhile, the pressure pad, constructed using Velostat—a pressure-sensitive, semi-conductive material—detects weight changes and acts as a safety mechanism for the feline as it enters and exits the enclosure.

The main PCB system acts as the bridge connecting the other four major systems. Components of the power system, specifically the voltage regulators, plug directly into the main PCB for power distribution. The rail system is directly controlled by the MCU via the motor driver, allowing manipulation of the sliding door. The optics system sends sensor data as input to the MCU for processing. Finally, the Pi system communicates with the MCU through UART (Universal Asynchronous Receiver-Transmitter), facilitating high-level data exchange between the MCU and the SBC.

2.8.2 The Pi System

The Pi system is dedicated to handling the computationally heavy task of AI-based animal identification as well as the user interface functionalities. This subsystem includes a Raspberry Pi, an IR Pi camera module, and a Pi-compatible LCD IPS screen. It is connected to the power system to receive regulated power and to the main PCB system via the UART interface.

This system's primary role is managing the AI-based animal identification functionality. The Raspberry Pi processes data from the IR camera module to identify animals using a lightweight machine learning model (LLM). Once identification is complete, the Pi triggers appropriate actions, such as opening the plexiglass door if a cat is detected. Additionally, the Pi system drives the LCD screen, which displays dynamic graphics and real-time statuses. The system also enables Bluetooth communication, allowing seamless data exchange between the Pi and the project's mobile app component.

2.8.3 The Optics System

The optics system ensures safety and efficient operation through two subsystems: an IR proximity sensor and an IR break beam sensor. Positioned on the outer front face of the enclosure, the proximity sensor remains active at all

times. Its purpose is to detect obstructions, such as an approaching object/animal, and trigger the entire system out of its low-power mode.

The break beam sensor, located across the opening of the enclosure, adds an additional safety layer. It monitors the entry path, ensuring that the plexiglass door does not close while a cat is entering. These sensors are powered by the power system (more specifically, the 5V regulator) and send their data to the MCU of the main PCB system.

2.8.4 The Rail System

The rail system provides the physical mechanism for controlling access to the litter box. This system consists of a motor, a threaded rod, two drive nuts, a plexiglass sheet, and a guard rail. The motor drives the threaded rod, causing the plexiglass door—clamped to the drive nuts—to slide horizontally, thereby opening or closing the cat door of the enclosure.

The guard rail, positioned at the bottom of the opening, prevents animals from pushing against the plexiglass door and letting themselves into the litter box. The rail system connects directly to the main PCB system, where the motor driver regulates both the power and control signals for the motor. Notably, the power system does not directly interface with the rail system, as power delivery is managed entirely by the motor driver.

2.8.5 The Power System

The power system supports the entire P.A.W.S. project by providing the necessary electrical energy for all components. It consists of a 12V AC/DC power supply and two buck converters: a 3.3V regulator and a 5V regulator. The AC/DC power supply converts standard 120Hz AC power from a wall socket into 12V DC power. The buck converters step down the 12V power to 3.3V and 5V as required by the various subsystems. The two voltage regulators plug into the main PCB.

This system powers the main PCB system, Pi system, optics system, and indirectly supports the rail system through the motor driver. Its robust design ensures efficient power distribution, preventing voltage fluctuations that could disrupt the system's operation.

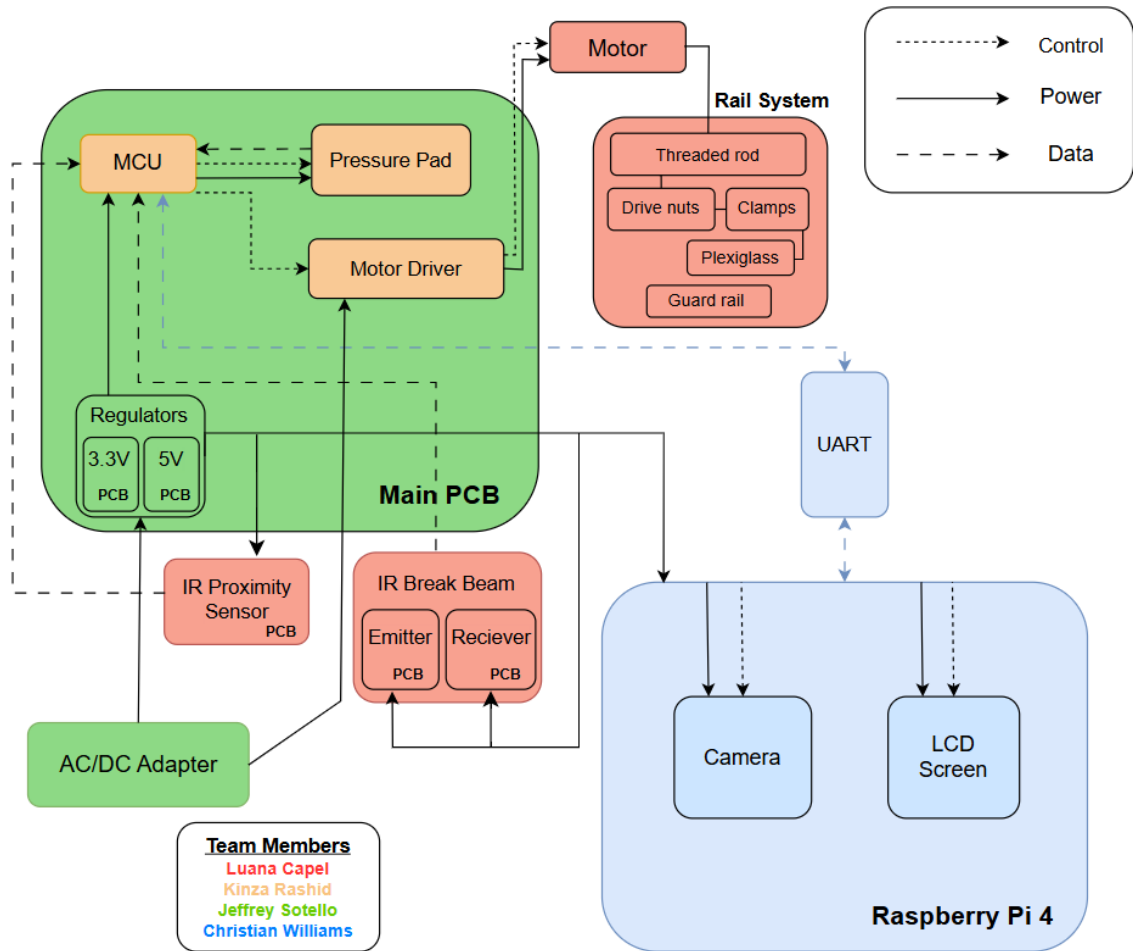


Figure (2.7) - Hardware Block Diagram.

2.9 Software Block Diagram

The P.A.W.S. enclosure is equipped with an infrared flood light that is constantly on (AC-powered). There is a signal added to the flood light, so when the flood light's radiation is reflected into the IR sensor (which means there's been movement close enough that enabled this light to be reflected), the IR sensor sends a message to the MCU, which uses UART communication to trigger the camera to begin sending a live video feed to a connected Raspberry Pi for real-time image processing. This enables the Raspberry Pi to remain in a low-power draw or off state in order to save battery life. During image processing, an AI object detection model will be able to determine if the movement in front of the enclosure is a cat, dog, or neither. The "neither" option includes any human or animal that isn't explicitly annotated in the training set as either a cat or a dog. If

this “neither” option is detected, then the system will simply do nothing and idle. If a dog is detected, the Raspberry Pi will communicate with the MCU to check if the door is open. If so, then the MCU will control the motor and close the door. Similarly, if a cat is detected and the door is currently closed, then the door will be opened. Additionally, the camera will take a picture and log the current time and date. This data is saved locally to be viewed within the integrated mobile app; the app’s functions are described above in section 2.9.2 and an early design mockup is shown in figure 2.4.

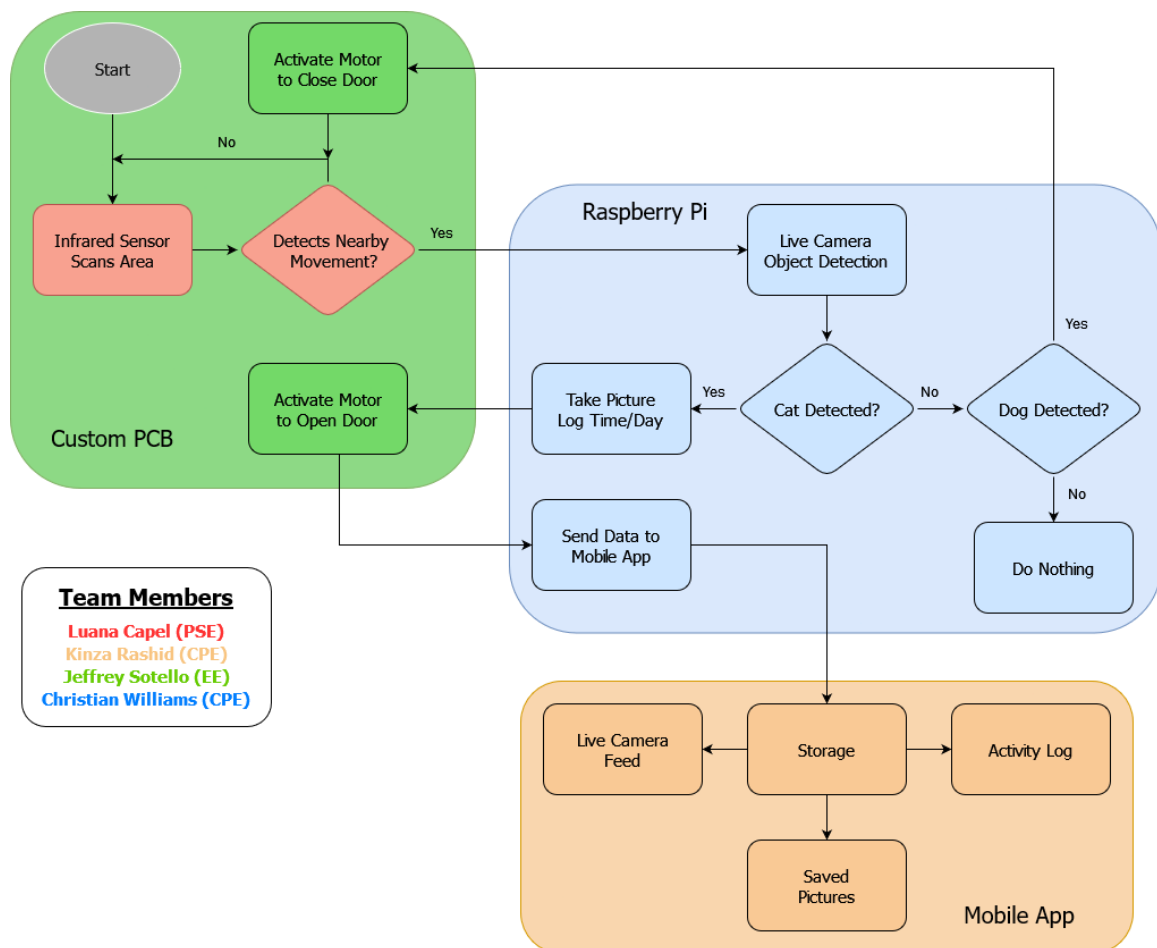


Figure (2.8) - Software Block Diagram.

2.10 House of Quality

The following subsection shows the House of Quality detailing the relationships when different engineering requirements and marketing requirements of the project.

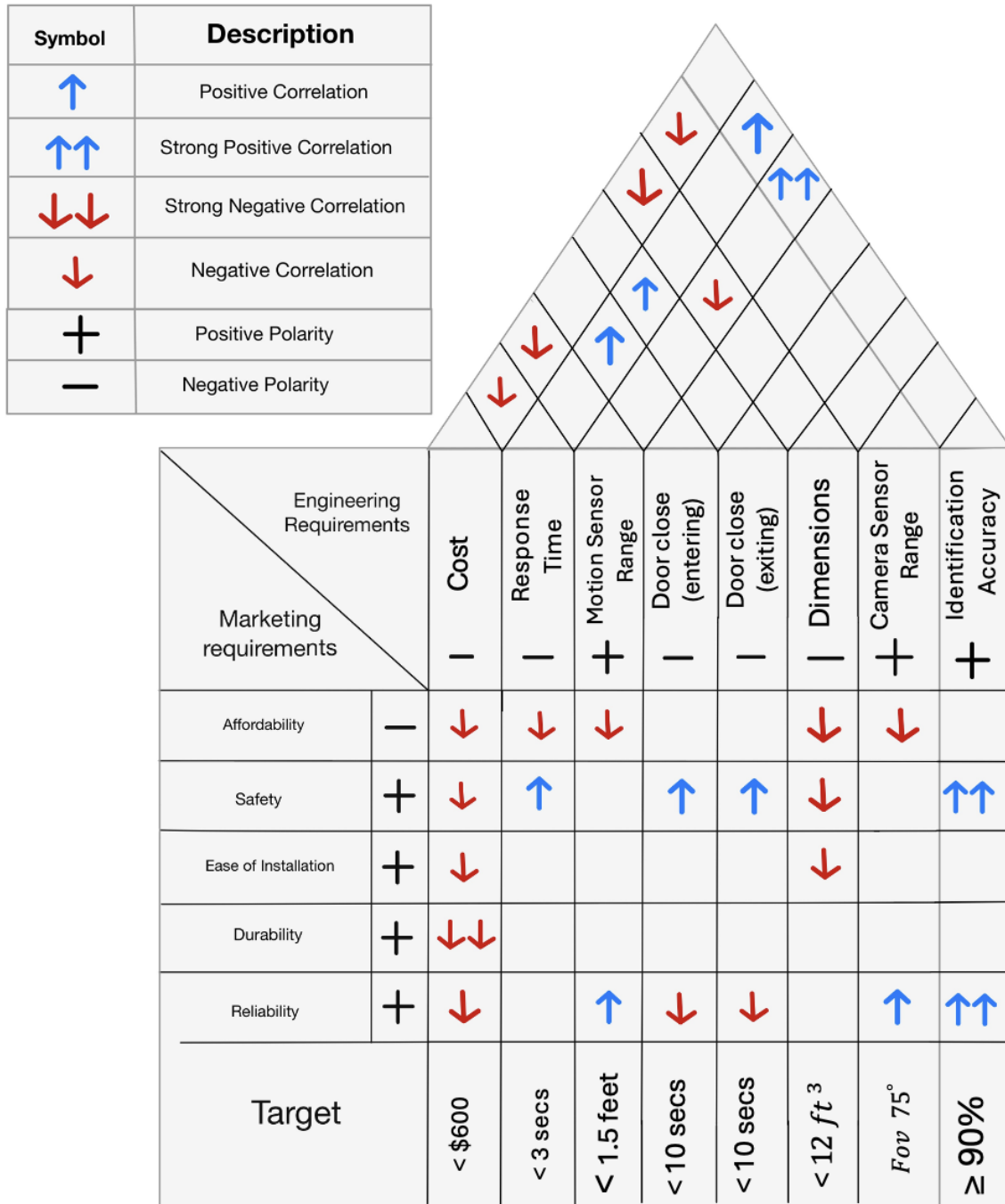


Figure (2.9) - House of Quality Diagram.

Chapter 3 - Research and Investigation

This chapter discusses the research and investigation that went into all the core components of the project, including both the hardware and software elements. It then details the specific technology and parts selected for the project.

3.1 Technologies

This subsection includes the research done on available chip technologies, machine learning technologies, motion detection technologies, motor technologies, display technologies, power sources and voltage regulation, optics technologies, and communication protocols.

3.1.1 Electronic Processing

Given the integrated nature of the electronics featured in this project, a logic chip is required. This logic chip must be capable of controlling a motor as well as processing data from multiple sensor inputs --two IR radiation optics systems and a pressure pad system. It must also be able to communicate with a SBC.

3.1.1.1 Major Chip Technologies

There are several major chip technologies to choose from, but for this project, two prominent chip technologies - microcontrollers (MCUs) and Field-Programmable Gate Arrays (FPGAs) - are explored and a comprehensive analysis of their features, applications, and suitability is built.

The two types are considered due to their unique capabilities and suitability for the task at hand.

Microcontrollers are known for offering a compact, integrated solution with built-in peripherals and low power consumption, making them ideal for embedded systems and IoT applications. They excel in tasks that require real-time control and processing of sensor data, which aligns well with the project's requirements for managing multiple sensor inputs and motor control.

FPGAs, on the other hand, provide a high degree of flexibility and parallelism in digital logic design. Their reconfigurable nature allows for custom hardware implementations that can be optimized for specific algorithms or signal processing tasks. This makes FPGAs particularly suitable for applications requiring high-speed data processing or complex digital signal processing, such as the IR radiation optics systems mentioned in the project specifications.

Both technologies have their strengths and trade-offs. Microcontrollers are generally easier to program using high-level languages and offer a more straightforward development process, while FPGAs provide superior performance for certain types of computations but require more specialized skills in hardware description languages.

The choice between these two technologies will depend on factors such as the required processing speed, power consumption constraints, development time, and the specific algorithms needed for the pressure pad system and PIR motion sensor integration. A thorough analysis of these factors in the context of the project's goals will guide the selection of the most appropriate chip technology.

3.1.1.2 FPGA

These are semiconductor devices that allow users to create custom digital circuits by programming them at a hardware level. They consist of an array of programmable logic blocks and interconnects that can be configured to implement complex digital functions. FPGAs offer high flexibility and reconfigurability, parallel processing capabilities, high-speed operation for specific tasks, a large number of I/O pins, the ability to implement custom hardware accelerators, and support for hardware description languages (HDLs) like Verilog and VHDL.

The core architecture of an FPGA comprises three main components: logic blocks, interconnects, and I/O blocks. Logic blocks, also known as Configurable Logic Blocks (CLBs) or Adaptive Logic Modules (ALMs), are the fundamental building blocks of an FPGA. They contain Look-Up Tables (LUTs), flip-flops, and other elements that enable them to perform a wide range of digital functions. LUTs implement combinational logic, while flip-flops provide storage for sequential logic.

Interconnects form a network of programmable routing resources that connect the logic blocks within the FPGA. This flexible routing system allows for custom connections between logic elements, enabling the implementation of complex digital circuits. I/O blocks interface the FPGA with external devices and signals, supporting various signal standards and voltage levels.

FPGAs are programmed using Hardware Description Languages and configured via a bitstream. This bitstream, generated through a process of synthesis and place-and-route, defines the FPGA's internal connections and logic. The configuration is typically stored in volatile memory, requiring the FPGA to be reconfigured at power-up, though some FPGAs offer non-volatile options for instant-on functionality.

Additionally, FPGAs are commonly used in telecommunications for signal processing and network routing, aerospace and defense applications such as radar systems and satellite communications, high-frequency trading systems, video and image processing, prototyping of ASICs (Application-Specific Integrated Circuits), and as machine learning accelerators. Their ability to perform parallel processing and be reconfigured in the field makes them particularly suitable for applications requiring high performance and adaptability.

3.1.1.3 MCU

These are compact, low-power integrated circuits that combine a processor core, memory, and various peripherals into a single chip. They are designed for specific tasks and are often referred to as "computers on a chip" due to their self-contained nature. Key features of microcontrollers include low power consumption, compact size, integrated peripherals such as timers, ADCs, DACs, and communication interfaces, real-time operation capabilities, cost-effectiveness for mass production, and ease of programming using high-level languages like C or C++.

The architecture of a microcontroller consists mainly of three components: the Central Processing Unit (CPU), memory (RAM and ROM), and peripherals (I/O, etc.). The CPU acts as the "brain", executing instructions stored in the program memory, processing data, and controlling peripheral operations. Its performance is determined by factors such as clock speed (measured in Hertz), architecture (e.g., Harvard or von Neumann), and the instruction set (e.g., RISC or CISC). Next, the memory is divided into two parts: program memory (typically non-volatile flash memory) for storing the instructions and the data memory (usually volatile SRAM) for storing variables and/or temporary data. The size and type of memory can differ greatly and significantly impact the microprocessor's performance and suitability across different applications. Lastly, the peripherals are additional integrated components that provide specific functionalities to the chip. Examples of such would be timers, counters, communication interfaces (like UART or SPI), analog-to-digital (ADC) converters, and Pulse-Width-Modulation (PWM) generators. All of these allow microcontrollers to interact with external devices and perform a vast array of tasks, from reading sensor data to controlling actuators. The availability and capabilities of these peripherals contribute significantly to the microcontroller's versatility and suitability for various embedded applications.

Programming microcontrollers involves writing code in high-level languages, compiling it into machine-readable instructions, and uploading it to the microcontroller's program memory. Development tools and environments,

including IDEs, debugging tools, and evaluation boards, facilitate the coding, debugging, and testing processes.

Microcontrollers find extensive use in embedded systems, including consumer electronics like remote controls and household appliances, automotive systems such as engine control units and anti-lock braking systems, industrial automation in PLCs and sensor networks, medical devices including patient monitoring systems and insulin pumps, and IoT devices like smart home sensors and wearable technology.

3.1.1.3.1 ESP32

The ESP32, developed by Espressif Systems, is a powerful, versatile microcontroller widely recognized for its integrated WiFi and Bluetooth capabilities, making it ideal for IoT (Internet of Things) applications. Espressif, a Shanghai-based company, launched the ESP32 in 2016 as the successor to its popular ESP8266. While the ESP8266 had already gained a strong foothold in the maker community due to its affordability and WiFi support, the ESP32 expanded on these features by adding dual-core processing, low power consumption options, and support for both WiFi and Bluetooth, including Bluetooth Low Energy (BLE). These enhancements allowed the ESP32 to serve a broader range of applications and establish itself as a standard in wireless microcontrollers.

One of the significant advantages of the ESP32 is its pre-certified module format, which includes an integrated antenna. This feature is particularly valuable for product developers because it eliminates the need to go through a separate FCC certification process for wireless communication compliance, reducing development time and costs. The ESP32 also offers several power management modes, making it adaptable for both high-performance and low-power applications. Furthermore, it has a wide range of peripherals, including digital and analog I/O, PWM (Pulse Width Modulation), ADC (Analog to Digital Converter), DAC (Digital to Analog Converter), and capacitive touch sensors, making it a versatile choice for projects requiring multiple interfaces.

With its extensive support in open-source communities and compatibility with various development environments like Arduino IDE and Espressif's own ESP-IDF, the ESP32 is user-friendly and widely adopted by both hobbyists and professionals. This balance of low cost, robust connectivity, and rich features has made this chip a popular choice for a wide array of applications.

3.1.1.3.2 MSP430

The MSP430 is a family of microcontrollers developed by Texas Instruments (TI), aimed primarily at low-power applications. Introduced in the 1990s, the MSP430 series was designed for battery-powered devices and applications where energy efficiency is crucial, such as sensor networks, medical devices, and consumer electronics. Texas Instruments invested heavily in developing this platform to address the need for a microcontroller that could operate efficiently at low power levels, a unique characteristic that quickly distinguished the MSP430 from other microcontrollers on the market.

One of the defining features of the MSP430 series is its ultra-low-power architecture, which includes multiple low-power modes that allow it to operate with minimal energy consumption when not actively processing data. This feature, coupled with its fast wake-up time, makes the MSP430 ideal for applications that require long battery life. Additionally, the MSP430 family includes a wide range of models, each catering to different needs. Some models offer integrated analog-to-digital converters, timers, and serial communication interfaces, allowing developers to choose a version that best fits their application's requirements without sacrificing power efficiency.

The MSP430 microcontrollers are easily programmable and are supported by Texas Instruments' Code Composer Studio (CCS), as well as other development environments. Texas Instruments provides a comprehensive suite of tools, including development boards, libraries, and online resources, making the MSP430 accessible to both beginners and experienced engineers. The MSP430's longevity in the market and its specialization in low-power applications have made it a trusted choice for applications where energy efficiency is a priority.

3.1.1.3.3 PIC

The PIC family of microcontrollers, produced by Microchip Technology, has a history that dates back to the 1970s. The PIC (Peripheral Interface Controller) architecture originated with General Instrument's PIC1640, which was initially developed as a simple controller for their own products. However, as the design evolved and was later acquired by Microchip Technology, the PIC microcontroller family became a foundational product line in the microcontroller market. Since then, PIC microcontrollers have grown into a broad family of chips used in diverse applications, ranging from industrial automation to consumer electronics and automotive systems.

One of the primary advantages of PIC microcontrollers is their wide range of models, which offer various combinations of features, memory sizes, and I/O

options. This diversity allows developers to select a PIC model tailored to their specific application requirements. PIC microcontrollers are also known for their robustness and stability, making them suitable for mission-critical applications. The architecture of PIC microcontrollers supports efficient execution of code, and many models include peripherals such as ADCs, PWMs, and UARTs, which reduce the need for external components.

PIC microcontrollers are typically programmed in assembly or C, and Microchip provides a range of development tools, including the MPLAB X Integrated Development Environment (IDE) and various debugging tools. PIC microcontrollers are also popular in the educational field due to their straightforward architecture and extensive documentation. Over the years, Microchip has expanded the PIC family to include both 8-bit and 32-bit models, catering to a wide array of applications and performance requirements. This adaptability and the PIC's longstanding presence in the market have solidified it as a reliable choice for embedded systems.

3.1.1.4 Logic Chip Comparison

In terms of performance, microcontrollers excel in sequential task execution and are well-suited for control applications with moderate processing requirements. FPGAs, on the other hand, offer superior performance in parallel processing and can achieve higher clock speeds for specific functions. Microcontrollers are designed for low power consumption, making them ideal for battery-operated devices and energy-efficient applications. FPGAs generally consume more power due to their complex programmable fabric, although recent advancements have improved their energy efficiency.

The development process for microcontrollers typically involves programming in high-level languages, which is more accessible to software engineers. FPGA development requires knowledge of hardware description languages and digital design principles, which can lead to a steeper learning curve and longer development cycles. FPGAs offer unparalleled flexibility, allowing for hardware-level customization and on-the-fly reconfiguration. Microcontrollers, while less flexible in terms of hardware configuration, offer software-level flexibility through firmware updates. In terms of cost, microcontrollers are generally more cost-effective for mass production and simpler applications. FPGAs tend to have higher unit costs but can be more economical for complex, low-volume projects or when hardware acceleration is required.

3.1.1.5 Conclusion

The microcontroller was selected as the primary logic chip for the P.A.W.S. project. Using this technology over FPGA provides the optimal balance of performance, energy efficiency, cost-effectiveness, and ease of development. The project's chip requirements, including motor control, IR radiation optics systems management, pressure pad system integration, and communication with an external processing body are all easily within the capabilities of modern microcontrollers.

As mentioned above, the MCU will be the "brain" of the linear rail system as well as the sensor processor for the optics. It will receive data from the optics systems and communicate this to the SBC, triggering the system to awaken if prompted. It will then actuate the motor to open and close the plexiglass door according to the SBC's return communication.

Among the ESP32, MSP430, and PIC options, the MSP430 emerges as the most suitable microcontroller for our application. While the ESP32 is feature-rich with its WiFi and Bluetooth capabilities, these wireless functions are not necessary for this project. The ESP32's connectivity features, dual-core processing, and wide range of peripherals would be underutilized in our design, making it a more complex and costly choice than needed. The additional capabilities of the ESP32 would add unnecessary complexity and power demands to the system, while offering no real benefit for our specific application.

The MSP430, on the other hand, is a more streamlined and efficient choice for this project. Known for its simplicity and low-power operation, the MSP430 has a straightforward architecture that meets all essential requirements. Its design is optimized for applications that prioritize efficiency and simplicity, which aligns well with our project's needs. The MSP430 offers just the right level of processing power and peripherals, such as ADCs, timers, and digital I/O, which are more than sufficient for handling the functions of the P.A.W.S. enclosure.

Particularly important for our application is the MSP430's robust UART communication capabilities. The microcontroller's built-in UART module makes it easy to establish reliable serial communication with the Raspberry Pi 5 SBC. This feature is crucial for our project as it enables efficient data transfer between the MCU and SBC without requiring additional hardware or complex programming overhead. The MSP430's UART implementation is well-documented and supported by Texas Instruments, making it easy to configure and optimize for our specific communication needs.

By choosing the MSP430, we can keep our hardware design lean and avoid potential problems associated with more complex MCUs. Additionally, our team has substantial experience working with MSP430 microcontrollers, which makes development faster and more reliable. This familiarity allows us to effectively program and troubleshoot the MSP430, giving us confidence in our ability to implement and optimize its functionality within the system. Texas Instruments' support resources, along with our prior knowledge of the MSP430's programming environment, will allow us to develop and refine the code efficiently.

3.1.2 Machine Learning Technology Comparison

This subsection discusses and cross examines the different machine learning technologies available.

3.1.2.1 Machine Learning Computational Platforms

The P.A.W.S. litter box project will perform real-time object detection and classification through a trained machine learning model that directly connects to a camera module's live video feed. This model will be capable of identifying the primary subject in the video to be either a cat, dog, or neither. Despite the rapid advancement in AI technology, real-time computer vision still requires substantial computing power that exceeds the capabilities of any current microcontroller alone. This necessitates the use of either an onboard single-board computer (SBC) or an online cloud-based computing service. With the recent surge of popularity in AI technologies, there are plenty of options to choose from on both sides.

3.1.2.1.1 Cloud-Based Computing Services

Cloud-based services provide several key advantages over onboard single-board computers. The most notable advantage is the ease of setup and use. For the P.A.W.S. project, using a cloud service would allow the camera to connect directly to the microcontroller, which could then wirelessly transmit data to an online platform. These AI platforms offer intuitive user interfaces, as well as easy access to an extensive list of APIs and documentation that can simplify both development and deployment.

Another important factor to consider is the scalability of both resources and storage. Cloud services typically provide access to powerful GPUs and TPUs (tensor processing units), enabling faster model training and object classification than any SBC can. For a smaller project like P.A.W.S., this means the system can adjust resource consumption based on its current needs. The same applies to its storage capacity as well. Live video feed can require a significant amount of data

storage at any time. While an SBC has limited storage space, a cloud service can easily accommodate high demands. Additionally, the intuitive user interface makes accessing and managing storage much easier on a cloud platform.

Some of the leading AI cloud services currently available include Google Vision AI, Microsoft Azure, and Amazon Rekognition.

3.1.2.1.2 Single-Board Computers

While cloud-based services excel in ease of use, power, and scalability, an SBC can offer its own advantages that possibly make it a better fit for the P.A.W.S. project. From a budgeting perspective, an onboard SBC is a straightforward one-time purchase, whereas most cloud services charge recurring monthly or yearly usage fees. A user may even incur additional charges if the amount of data to process is too large.

For the P.A.W.S. project specifically, the most compelling reason to choose an SBC over a cloud service is its ability to function offline. This capability allows the litter enclosure to continue operating in any environment where an internet connection is unreliable or completely unavailable. Additionally, because the SBC would be physically contained within the enclosure, it has a direct connection to both the microcontroller and the camera. This results in significantly lower latency and more immediate communication between the three components.

3.1.2.1.3 Computing Platform Comparison and Selection

The most important factors to consider for the P.A.W.S. project are cost, computing power, and power consumption.

Cost-wise, cloud-based services are typically subscription based with a low upfront cost, but high cost over time. SBCs are the exact opposite: high upfront cost with a low cost over time, because they only need to be purchased once. P.A.W.S. has a fairly limited budget that is already being stretched by the numerous other required parts. Because this project time scale is expected to last upwards of nine months, it makes more sense to pay the one-time fee for a single-board computer rather than paying for nine months of a subscription fee.

Computing power is a fairly easy comparison with a clear winner. Although P.A.W.S. uses a simple machine learning model that could be run on an SBC, cloud-based services are simply far more powerful. The entire purpose of these services is to provide computing power that no average developer would have access to. Any cloud-based option available will be more powerful than even the strongest available SBC, and so cloud-based is the obvious choice here.

Finally, power consumption is the least obvious comparison to make, as cloud-based services technically use a third-party to do all of the project's computing. The SBC is an added piece of hardware that has its own power requirements, whereas the cloud-based option would simply send data through the microcontroller that is already included in the project. Power consumption through a cloud service is loosely tied to the cost factor, as with more computing done through the service, a user could be charged for a higher tier of service. P.A.W.S. is fairly low power, so this is unlikely to happen at least. Cloud-based is the winner in regards to power consumption, as it doesn't add that extra piece of hardware.

For the P.A.W.S. project, the cost is the single most important deciding factor. A single-board computer is the clear winner in this regard, but also loses in the other two factors: computing power and power consumption. However, the machine learning tasks required by the project are fairly simple and don't necessarily require the computing power that a cloud service would provide. Through research on various SBC parts, we found that most notable SBCs would be able to easily handle the computer vision tasks required for P.A.W.S. After also considering the various methods of powering the enclosure, it was also decided that the power consumption from an extra SBC would not significantly affect the low-power requirements. After evaluating the scope of the project and its requirements, it was ultimately determined that P.A.W.S. should utilize a dedicated onboard single-board computer. While cloud services do provide tempting advantages over an SBC, they would overall be better suited for a large-scale production project rather than a smaller educational project such as P.A.W.S.

3.1.2.2 Machine Learning Frameworks

A machine learning model is an algorithm that learns patterns from a given dataset and uses these patterns to make inferences. In the case of P.A.W.S., the model will be trained on a large dataset of cat images and will then be able to determine whether the camera is detecting a cat or not. Frameworks are software platforms that provide the tools and libraries necessary for training and deploying these models. They typically include functions for data processing, defining the neural network's architecture, optimizing the training process, and deploying the fully trained model.

3.1.2.2.1 PyTorch

PyTorch is a framework developed by Meta (formerly Facebook) and released in late 2016. It is based on a much earlier open-source machine learning library known as Torch, released in 2002. As of 2022, PyTorch's development is now run

by an independent organization known as the PyTorch Foundation, a subsidiary of the Linux Foundation. In 2023, they went on to release PyTorch 2.0, an overall faster, more efficient, and more scalable major version. This framework is one of the most popular currently available for developers. As a result, there is extremely strong community support, with plenty of official and unofficial documentation, examples, and tutorials.

The PyTorch framework has interfaces for developers in both the Python and C++ languages. However, as the name would suggest, Python is the more up-to-date and robust version. The interface is built around being intuitive and user-friendly, while remaining deep enough for experienced developers to complete complex tasks. A key feature that PyTorch provides in the interface is a dynamic computation graph. This graph is built as operations are executed during runtime, allowing a developer to see in real-time what the program is currently doing, and where any errors might arise. This significantly decreases the difficulty of the debugging process.

For the P.A.W.S. project, PyTorch is an especially compelling standout choice among the other options presented. The framework has strong support for computer vision tasks that P.A.W.S. would need, such as image classification and object detection. Integrating the supported torchvision library would simplify the entire process of both developing and deploying the detection neural network. Perhaps the only downside to PyTorch is the relative newness of PyTorch 2.0 compared to the other major popular framework, TensorFlow. Although development may be far easier in PyTorch, full-scale deployment and optimization will likely be more challenging.

3.1.2.2.3 TensorFlow

TensorFlow is currently one of the two most popular machine learning frameworks alongside PyTorch. It is a free and completely open-source framework developed and released by the Google Brain team in late 2015. A second major release version, TensorFlow 2.0, was released in 2019, providing many new features and optimizations for neural network development. The library is primarily designed for larger-scale machine learning applications. Similarly to PyTorch, TensorFlow's popularity has led to extensive community support, both official and unofficial.

Although TensorFlow 2.0 is the newest and most powerful version available, the P.A.W.S. project would likely use the more lightweight TensorFlow Lite version. The Lite version was created specifically for mobile and embedded devices. It is slower and weaker than its 2.0 counterpart, but also draws less power and takes up less storage space; this is particularly useful for devices with low storage or RAM capacity, such as a microcontroller.

One of the primary development focuses for TensorFlow is optimizing it for full production deployment. Out of the options presented here, this framework is the easiest and most efficient in this regard. Development of a neural network that can complete computer vision tasks is more difficult, however. TensorFlow's API is comparatively more complex and less intuitive for beginners, with a less user-friendly interface. TensorFlow does give the user more control over coding with its large list of supported languages. It is primarily focused on Python and C, but can also implement C++, Java, JavaScript, Go, and Swift.

3.1.2.2.4 Keras

Keras is another open-source framework released not too long before TensorFlow in 2015. Although it was originally developed as an independent library, it is now directly implemented as an official high-level API in TensorFlow and can also support other frameworks like PyTorch. It has less direct community support than the previous two options but was designed to be easy to use and intuitive for beginners in machine learning.

The Keras API provides a simple interface that can allow a developer to start building a neural network quickly and easily. This is especially useful for managing early prototypes of the animal detection model. In addition, Keras includes a few pre-trained models to start development and testing, with the ability to retrain them for specific needs later. This framework is widely used for image classification tasks and identifying the objects within, which is exactly what P.A.W.S. will accomplish.

What makes Keras really stand out among the other options is that it doesn't have to be an exclusive choice. Because the Keras API can directly integrate with TensorFlow, it is possible to use TensorFlow's powerful backend libraries in combination with Keras' user-friendly intuitive interface. This eases the normally difficult development process when using TensorFlow and allows quick iterations on prototype models.

3.1.2.2.5 FastAI

FastAI is an open-source deep learning library released in late 2016 by the non-profit research group fast.ai. The goal of the group is to provide free online courses for developers just beginning to learn how to use deep learning. To help accomplish this, the fast.ai group released FastAI, which is a ML library built on top of PyTorch. The library provides a high-level API, meaning that it is more generic and intuitive, but does not have the ability to finely control low-level specific details. Because FastAI uses primarily high-level APIs and abstractions,

the framework is very approachable for beginners and allows building models to be simple and quick.

This framework also has integrated data handling, which vastly simplifies the process of handling large amounts of data. FastAI has prebuilt functions for loading and transforming large datasets that would be especially useful in training the P.A.W.S. model for image classification of animals. Similarly to Keras, FastAI is particularly useful for performing quick iterations on prototype models.

Because the fast.ai group is a nonprofit learning organization, FastAI has an extensive set of official support that includes courses and documentation. It does have an overall lower level of community support than previous options, however. Their focus on deep learning image classification suits the P.A.W.S. project well and makes FastAI a very compelling option.

3.1.2.2.6 RoboFlow

RoboFlow is different from the other options in that it is an online platform specifically designed for managing computer vision applications. With the online website, it is technically possible to create and fully train a model without touching any coding software. This obviously makes RoboFlow the easiest and most streamlined option available. A notable problem, however, is that this option is the only one presented that is not entirely free. This is a for-profit subscription based online platform that can be used for free in a limited amount, but depending on the workload could incur a significant cost. Fortunately, it is built off popular open-source libraries, so it is possible to recreate locally with help from the ML community.

The RoboFlow website was created to streamline the entire ML process from conception to deployment. Users are able to upload, annotate, and sort images all in one program. These images can then be directly used to train models and later export them across various formats such as TensorFlow and PyTorch. For beginners, this is by far the fastest and easiest method to deploy models for computer vision tasks. The most notable major limitation of RoboFlow is that it is only suitable for computer vision tasks and nothing else. This is not a problem for P.A.W.S. at least, but it is worth considering for the future, nonetheless.

3.1.2.2.7 Machine Learning Framework Comparison

All the frameworks listed above would work perfectly for P.A.W.S., however each does have its own distinct advantages and disadvantages. Because FastAI and Keras are additional compatible libraries, we have three main choices for the framework: PyTorch, TensorFlow, and RoboFlow.

When considering which framework to use, RoboFlow is an easy option to eliminate early. It's quite an intuitive online tool, but does not provide the level of in-depth tuning required for this project. In addition, using this service would incur an additional cost that, if necessary, we would prefer to avoid. Ultimately, however, the most penalizing aspect of RoboFlow is that it would simply make the process too easy for a senior design project. This service does everything from training to deployment with minimal input and no coding, making it a poor choice for a final project meant to demonstrate knowledge. For these reasons, RoboFlow is no longer in consideration for P.A.W.S.

PyTorch and TensorFlow are the two most popular machine learning frameworks available right now. While both are highly regarded in the industry, PyTorch has been gaining more popularity relative to TensorFlow. Both have excellent community support, so finding examples, tutorials, and documentation will be quick and easy with either option. Each framework is specialized for a different part of the computer vision workflow. PyTorch is especially useful during the development and prototyping stages with its intuitive UI and torchvision library. TensorFlow is better suited for end-stage full deployment of a trained model on a larger scale.

Ultimately, the deciding factor on which framework to choose for the project comes down to a factor not yet discussed: the machine learning model. As discussed later in the paper, the chosen model for the project is called YOLOv10. This is a great pre-trained model built specifically for object detection and inferencing tasks like P.A.W.S. Although the YOLO models can be converted to TensorFlow format with a tool called ONNX, they are primarily built upon and natively support PyTorch. For this specific reason, the team has chosen to use PyTorch as the backend framework for the project.

Finally, we need to choose between solely using the PyTorch backend or adding additional supported libraries like FastAI or Keras on top. Despite both being solid, compelling options, neither was chosen for this project. FastAI was not chosen as a result of its rigidity. Although it has the best official documentation and most intuitive UI, FastAI is ultimately a high-level API that does not allow a developer editing access to the finer details of the model. Keras was the most enticing option to combine with PyTorch, but was also not chosen simply for a lack of support. While PyTorch as a backend has an excellent official and community support network, the frontend library Keras lacks either. It would still be possible to build the P.A.W.S. codebase with Keras, but would be significantly more difficult and

end up with fairly similar results. For these reasons, P.A.W.S. will solely use the PyTorch backend as the framework.

3.1.3 Pressure-Sensitive Conductive Sheet

Velostat, also known as Lingstat, is a specialized polymeric material typically used for packaging sensitive electronic components to protect them from static discharge. This conductive polymer film is made from polyolefins infused with carbon black, which gives it a unique electrical property. The resistance of Velostat decreases steadily as more pressure is applied. This pressure-sensitive characteristic allows it to function effectively as a sensing material, particularly in pressure and touch sensors.

When a force is applied to Velostat, the carbon particles within the material are compressed, reducing electrical resistance. This property makes it ideal for DIY and educational projects, where it can be easily integrated into circuits to detect pressure, force, or weight. For instance, Velostat is frequently used to create simple force-sensitive resistor (FSR) setups, allowing users to measure varying degrees of applied pressure through changes in resistance.

Due to its thin, flexible nature, Velostat can be incorporated into various form factors, from wearable sensors to pressure-sensitive mats. In robotics, it can provide tactile feedback for grippers or detect pressure in soft robotics applications. It is also used in biomedical engineering for low-cost, flexible sensors that measure contact or pressure in rehabilitation devices. Additionally, Velostat's anti-static properties make it useful in environments where electronics are susceptible to electrostatic discharge, while its low-cost and widely available nature have made it a popular choice for hobbyists and professionals alike. Numerous resources and tutorials are available online, guiding users on how to utilize Velostat for different sensor applications.

3.1.4 Motor

Selecting the appropriate motor technology for the horizontal sliding motion of the plexiglass door is crucial, as this component acts as the access barrier to the litter area and ensures proper system operation. To make an informed decision, a comprehensive analysis of various motor technologies was conducted, considering factors such as power requirements, precision, cost-effectiveness, and compatibility with the overall system design.

3.1.4.1 Major Motor Technologies

There are two major categories that all motors fall into, AC and DC motors. These derive their classifications from their respective power sources: alternating current and direct current. While AC motors generally exhibit superior torque generation due to their ability to handle higher current loads, DC motors often offer greater efficiency in energy utilization. Both motor types span a diverse range of power outputs and form factors, catering to various industrial applications. The selection between AC and DC motors typically hinges on specific performance requirements, power availability, and system integration considerations within a given operational context.

3.1.4.1.1 AC Motors

These motors usually have low startup power demands, controllable starting current levels and acceleration, easily integrate-able add-ons that control speed/torque, high durability, long life spans, and capabilities for multi-phase configurations. There are two common major categories of AC motors.

3.1.4.1.1.1 Induction/Asynchronous

These motors are widely used in industrial applications due to their simplicity and robustness. They operate on alternating current and are known for their reliability and low maintenance requirements. These motors offer high efficiency at full load, simple construction, and are suitable for high-power applications. However, because of the required AC power source, they can be complex to control in terms of speed, and are less efficient at lower speeds.

3.1.4.1.1.2 Synchronous

These motors operate at a fixed speed synchronized with the AC power supply frequency. They are often used in applications requiring precise speed control. These motors boast excellent speed stability, high efficiency across the speed range, and good power factor. On the downside, they are more complex than induction motors, typically require a DC excitation system, and are not suitable for the DC-powered system of the project.

3.1.4.1.2 DC Motors

DC Motors are relatively simple to install and maintain, featuring high startup power and torque, fast response times for starting, stopping, and acceleration, and availability in several standard voltages. Three common DC motor technologies were cross-examined.

3.1.4.1.2.1 Brushed

These are simple and inexpensive, making them popular in many low-power applications. They offer simple speed control, low initial cost, and a wide speed range. However, they require periodic maintenance due to brush wear, have lower efficiency compared to brushless alternatives, and can generate electrical noise.

3.1.4.1.2.2 Brushless/BLDC

These offer several advantages over their brushed counterparts, making them increasingly popular in various applications. They boast high efficiency of 90% or more, long lifespan due to the absence of brushes, and excellent speed-torque characteristics. The main drawbacks are the need for more complex control systems, higher initial cost, and the requirement for electronic commutation.

3.1.4.1.2.3 Servo

These DC motors are designed for precise position control and are commonly used in robotics and automation. They offer extremely precise position control, high responsiveness, and have an integrated feedback mechanism. However, they are often limited to less than 360-degree rotation, require complex control systems, and come at a higher cost due to their integrated components.

3.1.4.1.2.4 Stepper

These motors provide precise position control without the need for feedback mechanisms, making them ideal for many positioning applications. They offer precise open-loop position control, high holding torque, and simple control for basic operations. Potential limitations include the possibility of missed steps under high loads, lower efficiency at high speeds, and resonance issues at certain speeds.

3.1.4.1.2.4.1 Magnet Mechanisms

Stepper motors can have several magnetic mechanisms, each one offering different advantages. The three types that will be discussed in this paper are permanent, variable reluctance, and hybrid types.

The oldest and more foundational magnet mechanism is the permanent magnet (PM) stepper motor, which employs a straightforward design featuring a permanent magnet rotor magnetized lengthwise with north and south poles. This configuration typically incorporates two to four main poles on the stator, each equipped with multiple teeth to achieve a fine step resolution. This motor works

through the magnetic poles of the rotor continuously seeking alignment with the energized stator poles, creating movement as the current alternates between poles. This design provides an excellent low-speed torque and maintains a natural detent torque even when unpowered. However, due to this aspect, this motor type generally operates at lower maximum speeds compared to other variants.

In contrast, the Variable Reluctance (VR) stepper motor takes a different approach, utilizing a soft iron rotor with multiple teeth. This motor type lacks any permanent magnets and its design relies on a multi-toothed structure in both the stator and the rotor. There are different teeth numbers between the two components, naturally creating air gaps. This mechanism operates on the principle of minimum magnetic reluctance, where rotor teeth automatically align with the energized stator to minimize the air gap. While this design eliminates detent torque when not receiving any power, it enables higher step rates and potentially smaller step angles, all while maintaining a lower cost due to the simple construction.

The Hybrid (HY) stepper motor represents the latest stepper motor evolution, combining the principles of both PM and VR designs. It features the most sophisticated structure out of the three types, incorporating a permanent magnet core magnetized axially that is complemented by multiple teeth on both stator and rotor components. There are typically 50 rotor teeth per stack. This combination harnesses both permanent magnet alignment found in PM motors and reluctance effects found in VR motors, with teeth providing precise positioning while magnets deliver increased holding force. The result is that the hybrid motor can offer high precision with typical 1.8-degree steps, substantial detent torque, and an impressive torque-to-size ratio.

3.1.4.1.2.4.2 Coil Winding Configurations

When it comes to coil winding configurations, the industry primarily employs two distinct approaches: bipolar and unipolar.

Bipolar configuration features a single winding per phase, typically utilizing four wires in total, with current capable of flowing in both directions through each winding. This arrangement demands more sophisticated H-bridge driver circuits but compensates users with maximum torque output for a given wire gauge as well as superior power efficiency. The bipolar design can typically deliver up to 40% more torque than its unipolar counterpart, though this comes at the cost of more complex driver circuits and control systems [CITATION].

The unipolar configuration takes a different approach, incorporating center-tapped windings that result in five, six, or eight wires depending on internal

connections. This design effectively creates two coils per phase with a common center point, allowing current to flow in one direction through half of each winding at any given time. While this arrangement sacrifices some performance metrics - utilizing only half the winding at any time and delivering lower maximum torque - it offers significant advantages in terms of simplified driver circuits and control logic, making it a preferable option for basic applications where cost and complexity are primary concerns.

The interaction between these magnetic mechanisms and winding configurations plays a crucial role in modern motor design. Contemporary hybrid steppers predominantly employ bipolar windings to maximize performance, while PM motors can accommodate either configuration but typically achieve optimal results with bipolar arrangements. VR motors, given their fundamental design principles, often pair well with simpler unipolar arrangements. These technical choices significantly influence the motor's ultimate performance characteristics, including precision, torque delivery, speed capabilities, and overall efficiency, making them critical considerations in motor selection for our project.

3.1.4.1.2.4.3 NEMA

Our research into stepper motors led us to discover NEMA, also known as the "National Electrical Manufacturers Association". They represent industry-standard mounting configurations. Their different standardized stepper motors have a numerical description attached to them (e.g. NEMA 17). The numerical designation in NEMA motors corresponds to the faceplate size in inches. NEMA 17 motors feature a 1.7-inch square mounting face and NEMA 23 motors feature a 2.3-inch square mounting face. This standardization ensures consistent mounting patterns and interchangeability across manufacturers, making them useful for both prototyping and production. For our project, we limit our extensive research to models to NEMA 17 and 23, as these are widely available and commonly used in precision motion control systems. The other models (e.g. NEMA 14, NEMA 42, etc.) were determined to be outside the required specifications for this project.

NEMA 17 motors typically deliver holding torque ranging from 0.3 Nm to 0.7 Nm, operating at the typical step angle of 1.8 degrees (or a step resolution of 200). They generally draw 1-2 amperes per phase and operate at voltages between 12V and 24V DC. This makes them ideal for lighter applications where space and weight constraints are the primary concerns. Their compact size and moderate power consumption also make them the de facto standard in desktop 3D printers and small CNC machines.

NEMA 23 motors, being physically larger, offer substantially higher torque capabilities -- typically ranging from 1.2 Nm to 3.0 Nm -- while maintaining the same step angle precision. They commonly operate at higher current ratings of 2-4 amperes per phase and can handle voltage ranges up to 50V DC in some models. This increased power capacity comes with a trade-off of higher power consumption and greater thermal management requirements. However, for applications requiring higher torque or increased positional accuracy under load, NEMA 23 motors often provide a more cost-effective solution.

3.1.4.1.3 Gearbox Consideration

While gearboxes can offer benefits such as increased torque and more precise control, it was determined that integrating a gearbox with the chosen stepper motor is unnecessary for this application for a number of reasons. The lightweight nature of the plexiglass door means that the stepper motor's inherent torque capabilities are adequate without amplification, even though geared steppers can achieve impressive torque outputs. The mechanical design minimizes friction, eliminating the need for the additional torque a gearbox would provide. Moreover, backlash issues that occur commonly with geared motors and reduce positioning accuracy when changing direction can be avoided.

Additionally, several motor types (such as the stepper motor) have a native step resolution that is sufficient for controlling the door's position without the need for further reduction through gearing. Not only that, but omitting the gearbox keeps the system simpler and more cost-effective, aligning with our fundamental project goals. We prefer a compact design and adding a gearbox would increase the overall size of the motor assembly. Last but definitely not least, by avoiding a geared solution, the system isn't limited to low RPM applications. This is important, as we want the plexiglass door to open and close fully within a maximum of 5 seconds. This would mean that if the plexiglass door is 9 inches wide, the motor would have to rotate the rod and drive the nuts fast enough to provide a linear speed of – at the very least – 1.8 inches per second.

3.1.4.1.4 Speed Consideration

For the project, the stepper motor will be actuating the opening and closing of the plexiglass cat door. The motor is part of a larger linear motion system, where it'll attach to a threaded rod which holds two drive nuts and the sheet of plexiglass. One of the product requirements of the P.A.W.S. project is that the motor must rotate at a speed in which the 9 inch wide plexiglass door is able to clear the 8-inch wide entrance into the enclosure within 5 seconds. This computes to a linear speed of around 1.8 inches per second. This is quite fast, so speed is a major consideration for the motor.

3.1.4.1.4.1 Parameters that Affect Motor Speed

When optimizing the stepper motor for high-speed performance, several critical specifications work together to determine the motor's maximum speed capabilities. A motor's dynamic torque characteristics plays a crucial role in determining its speed ability. The torque-speed curve, which shows how the motor's torque decreases with increasing speed, is particularly significant, as a motor with a flatter torque-speed curve will maintain better performance at higher speeds even with lower holding torque specifications than other motor options.

The motor's inductance is also another critical specification for speed prioritization. Lower inductance allows for faster current changes in the windings, enabling higher step rates, and motors with inductance values below 5 mH (milli-Henry) generally perform much better than those with higher inductance. This is because lower inductance allows the current to build up and collapse more quickly in the windings, essentially enabling faster step rates without losing steps.

Step angle and resolution also play a role in speed optimization. While smaller step angles (like 0.9° versus 1.8°) provide finer positioning control, they require twice as many pulses to achieve the same rotation speed. This means the driver must operate at higher frequencies, which can become a limiting factor. Therefore, for pure speed applications where fine positioning isn't critical, motors with larger step angles might actually be advantageous. Therefore, all the motor models that will be considered for use in the project will have a step resolution of 1.8 degrees.

The rotor inertia specification usually becomes more important at higher speeds as well. A lower rotor inertia allows for faster acceleration and deceleration, which enables a better response to rapid speed changes. However, this must be balanced against the load inertia. This is not as important for the project, as rapid speed changes are not present in the linear rail system. Rotational easing will be implemented for the cat door to smoothly open and close.

Current rating and voltage specifications are also crucial for high-speed operation. Higher voltage ratings allow for faster current rise times in the windings -- which is essential for maintaining torque at higher speeds -- while the rated current determines the maximum torque available. However, it is the voltage headroom above the rated voltage that often determines how well that torque can be maintained at speed. Modern drivers often use voltages much higher than the motor's nominal voltage to improve high-speed performance.

The motor's construction type also influences speed capabilities. Hybrid stepper motors typically offer the best high-speed performance due to their optimized

magnetic circuit design. Therefore, all the motor models that will be considered for the project will have the hybrid magnetic mechanism.

When all these specifications are considered together and multiple stepper motor models available on the market were found that fit these specifications (refer to Table 3.X in Section 3.2.3). These motors feature high torque, lower inductance, moderate step angle, and lower phase resistance. The key is finding the right balance of these characteristics for our specific requirements.

3.1.4.2 Motor Technology Comparison

While BLDC motors offer high efficiency and smooth operation, their complex control requirements and higher cost make them less suitable for the project. The need for specialized controllers and the potential overkill in terms of speed capabilities outweigh their benefits for the relatively simple door movement of the linear rail system.

Servo motors initially seemed promising due to their precise control capabilities. However, several factors led them to be ruled out. Many servo motors are restricted to less than 360 degrees of rotation, which greatly limits the door's travel range. Additionally, the integrated feedback mechanisms – while beneficial for some applications – add unnecessary complexity to the system.

3.1.4.3 Motor Technology Conclusion

After careful consideration, it was determined that a stepper motor will offer the best balance of features for the motorized linear rail system. Stepper motors provide accurate position control without the need for complex feedback systems, which is crucial for reliably opening and closing the plexiglass door. Compared to servo and BLDC motors, stepper motors offer a good balance of performance and affordability, aligning with the project's budget constraints.

The relatively simple control requirements of stepper motors reduce the overall complexity of the system, potentially improving reliability and ease of maintenance. Stepper motors can maintain position without power consumption, which is beneficial for keeping the door securely closed or open when needed. Unlike some motor types that lose torque at low speeds, stepper motors maintain high torque even at low rotational speeds, ensuring smooth door movement throughout its range of motion. Stepper motors are also known for their robustness and long operational life, which is crucial for a household appliance like the project. They are also easily integrated with microcontroller-based systems, aligning well with the use of chip control.

3.1.5 Display

A display is crucial for enhancing user experience. This display will enable users to log litter-cleaning times and monitor pet usage efficiently. To determine the most suitable display technology for the project, a comprehensive comparison was conducted, considering factors such as functionality, cost-effectiveness, and compatibility with system requirements.

3.1.5.1 Basic Display Technology

Several different display technologies were cross-examined. Starting with the most basic display technology, 7-Segment displays are simple, cost-effective options primarily used for displaying numerical data. While they excel in showing numbers and basic characters, their limited output variety makes them unsuitable for the project's diverse display needs. There is also the LED Dot Matrix Displays, which offer more flexibility than 7-Segment displays, allowing for the representation of letters, numbers, and simple graphics. However, they still fall short of providing the rich user interface required for the project.

3.1.5.2 Liquid Crystal Display

Next, Liquid Crystal Display (LCD) technology was considered. Despite being older technology, it remains a popular choice for many applications. LCDs offer several advantages that align well with the project requirements. The first is resolution flexibility. LCDs can display a wide range of resolutions, accommodating various information layouts. Another is an integrated backlight. This feature ensures visibility in low-light conditions, crucial for indoor and night use. Another very important parameter is cost-effectiveness. LCDs provide a good balance of functionality and affordability. Lastly, they are highly energy efficient. Their low power consumption aligns with the project's energy conservation goals. While LCDs have known limitations such as poor performance in extreme cold and narrow viewing angles, these drawbacks are negligible for our indoor application where temperatures remain moderate and users interact with the display at close range.

3.1.5.2.1 TFT Liquid Crystal Display

TFT LCDs represent an advancement over traditional LCDs, offering improved color reproduction and response times. There are three main types of TFT LCDs, each with distinct characteristics.

The first type is known as Twisted Nematic (TN). It's known for high response times, making them ideal for applications requiring rapid screen updates. The

second type is called In-Plane Switching (IPS). It offers superior color accuracy and wider viewing angles compared to TN panels. The last type is Vertical Alignment (VA). It provides a good balance between TN and IPS, with better contrast ratios.

3.1.5.3 Organic Light-Emitting Diode Display

There are also advanced display technologies such as Organic Light-Emitting Diode (OLED). They offer several compelling advantages such as true black reproduction, energy efficiency, and wide viewing angles. By eliminating backlighting, OLEDs can achieve perfect black levels, resulting in vivid colors and high contrast ratios while also consuming less power when displaying the darker content and allowing an ultra-thin display profile. Additionally, the fast response times are ideal for displaying rapidly changing information, increasing customer satisfaction. Despite these benefits however, the high cost of OLED displays makes them less suitable for the budget-conscious project.

3.1.5.4 Electronic Paper

In the vein of power efficiency, the E-paper (or Electronic Paper) display technology cannot go unmentioned. These displays offer unparalleled power efficiency, consuming energy only when updating the display content. However, they present significant drawbacks for the application due to a lack of a backlight and slow refresh rates. E-Paper displays rely on ambient light, making them difficult to read in low-light conditions and the sluggish screen updates could frustrate users accustomed to responsive interfaces. Therefore, the E-Paper display is not considered unsuitable for the interactive system requirement for the project.

3.1.5.5 Display Technology Conclusion

After careful consideration, the TFT LCD with IPS (In-Plane Switching) technology was chosen for the project. This decision was based on several key factors that make IPS displays an ideal fit for the interactive user system. Superior color reproduction and wide viewing angles are offered by IPS, enhancing user experience, while seamless integration is ensured by its high compatibility with Raspberry Pi, reducing development time and potential issues. Despite providing excellent visual quality, these displays remain relatively affordable, aligning with the goal of creating an accessible and sustainable solution. User interaction is simplified by the easy touch screen capabilities that are often included with many IPS displays. While not as energy-efficient as E-Paper, less power is consumed by IPS displays compared to OLED alternatives. The need for frequent replacements is reduced due to the durability and long lifespan for which these

displays are known. Additionally, this display type is easily integrated into a design such as the enclosure's, as these come in a wide range of sizes and resolutions.

3.1.6 Power Source

The power source is an important selection as it provides the necessary power for each component of our system to function properly. In this case for P.A.W.S., the power source will drive essential parts such as the camera, sensors, motor, and microcontroller. There will be different levels of delivered power depending on the component, for example the motor that is responsible for moving the door may draw the most power, while the motion detect sensors require less. For our system, it is essential that we properly regulate the power, ensuring each part receives the correct voltage and current to avoid malfunctions, such as slow or incomplete door movements and sensor failures. To keep all of the components running efficiently we will choose a reliable, stable power source that can continuously support a safe and consistent operation of our system.

3.1.6.1 Direct Current (DC) - Rechargeable Batteries

The first idea we had as the solution to the power source of our system was to use rechargeable batteries. Since our system is running at low DC power, this will give us flexibility to choose battery specifications that are compatible to our operating needs. The most common option for rechargeable batteries we may consider using would include lithium-ion (Li-ion) batteries. Li-ion batteries in general have a higher cost initially, but come with less maintenance and a longer lifespan. We would be able to simply disconnect and swap out batteries when necessary, and charge them using a docking station. The main advantage of this is it allows portability of the litter box to be located anywhere the customer desires in the house.

3.1.6.2 Alternating Current (AC) - Outlet

The second solution we thought of as the power source would be an AC power source provided through a wall outlet in the house. Typically, the power supplied through a common household outlet can yield a maximum capacity of 1800 or 2400 Watts, that equates to 15 or 20 Amps of current at 120 Volts. This is an excessive amount of voltage since our components operate at lower DC voltages. First of all, we will need to convert the supplied AC power from the outlet into a safer, lower DC voltage. To do this we can implement an AC-DC power supply adapter that will convert the voltage for us. Next, we will need to step down the voltage significantly by using a voltage regulator, which we will go into more detail about later on how we utilize the regulator and which regulator will best fit the system. Overall, the AC power source option is reliable while the house has power

available and would be a cheaper resource in the long run of the system's operation. The main drawback of using a wall outlet for the power source would be limiting the customer's options for the location of the litter box in the house as it would need to be plugged in at all times.

Table (3.1) - AC and DC comparisons.

Aspect	Rechargeable Battery	Outlet
Cost	\$20-\$100 Battery Pack	\$20 Adapter + Long term AC-DC power consumption cost
Maintenance	Periodic Battery Replacement	Minimal Oversight
Efficiency	85-95%	95-99%
Reliability	Moderate depending on battery charge	Continuously high as power is operational
Location Convenience	Highly Portable	Fixed Location to power outlet

3.1.6.3 Conclusion

After careful consideration, choosing AC power as the power source is simply the best option where uninterrupted operation is essential, and this would give us the most reliable and low-maintenance outcome. Since there is no need for battery replacements or recharging, this will keep costs low in the long run while continuously supplying the power we need.

3.1.7 Optics

Infrared (IR) light represents a portion of the electromagnetic spectrum that occurs just beyond the visible spectrum. Its wavelengths range from about 700 nanometers (nm) to 1 millimeter (mm), but this range is often divided up into three regions: near-infrared, mid-infrared, and far-infrared. Although IR light is undetectable to the human eye, it can be sensed as "heat" by many materials and

types of sensors. The most common use for IR radiation is in remote controls. Other applications for IR sensors include night vision cameras, thermal imaging, and an assortment of different kinds of "smart" sensors that know how to "read" IR light.

Let us consider a break beam sensor, one of the subsystems for our project. In this device, an infrared light beam is emitted in a straight line from an LED. When an object moves into the path of this beam, it serves to break the beam, indicating to a detector that an object is present or moving.

There are several advantages to using infrared (IR) light for building a proximity sensor[5], compared to using other wavelengths, like visible light. The longer wavelength of infrared light makes it less susceptible to interference from ambient lighting conditions, although not perfect because ambient light does include IR, especially sunlight. This trait makes the infrared proximity sensor reliable in different environments, particularly in indoor settings. Another advantage is that the infrared light is invisible to human eyes; thus, a person using a device equipped with proximity sensors will not "see" the light being used for the sensor function[6].

Another major advantage is the energy efficiency of infrared LEDs. They are much like regular LEDs in that they are very efficient. But they are more efficient than even the best regular light-emitting diodes. They consume less power than other light sources, making them ideal for battery-operated devices. Proximity sensors with infrared LEDs also have a good balance of range and precision, if the ambient conditions are not too bright. And all the basic components you would need for an infrared LED-based proximity sensor are cheap and easy to find[7].

The fact that infrared light can penetrate certain materials that visible light cannot gives the sensor even more possible uses[8]. From these abilities come a lot of other good things: performance that is hard to beat, efficiency that is hard to match, and practicality that is hard to question. When you add up all these factors, the choice to use infrared light for a proximity sensor becomes almost a no-brainer.

3.1.7.1 LEDs vs Laser Diode

There are several practical reasons for using an infrared light-emitting diode (LED) instead of a laser diode in a proximity sensor, particularly concerning safety, simplicity, and cost[9]. For one thing, infrared LEDs are much safer when it comes to eye exposure, a real concern for many proximity sensing applications where pets might be nearby. Laser diodes, on the other hand, emit a concentrated light that could easily damage the retina, even at low power levels that normally

wouldn't be harmful[10]. In applications where pets are likely to be in the path of the emitted light, an IR LED is a far safer bet. If you just look at the cost, IR LEDs usually cost a lot less than laser diodes.

When it comes to performance, IR LEDs generally produce a wider beam. This characteristic can be advantageous for proximity detection, as it allows the infrared LED to cover a broader area compared to the narrower beam of a laser diode. Laser diodes are more precise and focused, but as has been pointed out, what you really want for proximity sensing is a source that's capable of broadly illuminating the "you are here" area without necessitating any kind of laser-like pinpoint accuracy[11].

In general, both technologies have their advantages. But when it comes to ease of use, lower cost, and safety, infrared LEDs are much more suitable for that run-of-the-mill proximity sensor, the kind of sensor that doesn't need to be super precise and can be installed right in the vicinity of the user. In the case of our project, we will have a proximity sensor at the entrance of the litter box to detect any movement within at least a foot of the doorway[12].

3.1.7.2 Photodetector

Selecting the best detector for a proximity sensor hinges on the precise application demands. The leading candidates—photodiodes, photoresistors, and phototransistors—each have their own range of useful applications as well as strengths and weaknesses. The best use case for photodiodes is light-intensity-change detection that requires quick responses and a high level of good, reliable sensitivity[13]. They are also good for applications requiring light-intensity change detection that demands linearity. The issue that arises for photodiodes is the possible need for extra amplification, meaning that the circuit may become more complex.

Light-dependent resistors (LDRs), which are also known as photoresistors, are simple and inexpensive. They are easy to integrate into circuits and do not need complex supporting electronics. However, compared to photodiodes and phototransistors, they have slower response times. This might limit their application to circuits that operate at lower speeds. Also, they're not very consistent. The sensitivity of the units can vary a lot, which obviously affects the consistency of devices that are made in large numbers[14].

Combining the best attributes of both photodiodes and photoresistors, phototransistors perform exceedingly well in light-detecting applications because they internally amplify the light signal, so there's no need for an external amplifier. This makes circuits simpler to design, like photoresistors. While phototransistors

are more sensitive than photodiodes, they are also slower, as they don't have the same linear response. This can lead to less precise light detection[15].

To sum up, if you want something that is fast and precise, go with the photodiode. If your priorities are simplicity and low cost, then a photoresistor is your best bet. For good all-around performance and a decent amount of sensitivity, you can't beat a phototransistor. For our project we decided to go with photodiodes because our main goal is speed, efficiency and cost.

3.1.7.3 Focusing Lens

There are several choices available when it comes to picking a lens for the light-magnifying part of a proximity sensor. Each option has its own set of characteristics and applications. For light magnification, the most common option is the convex lens, which can take the form of plano-convex or bi-convex. These lenses are good at converging light to a focal point, which is what is needed for many light-magnification applications. But they're not the only options and not always the best ones. Fresnel lenses are flatter, lighter, and more compact than traditional convex lenses. That's why they're often used in designs where space and weight are concerned.

A concave lens is another option to consider, they are thinner at the center than at its edges, causing light rays to diverge as they pass through it. This divergence makes concave lenses particularly useful for applications requiring light to spread out, such as expanding or redirecting beams for a broader field of view. In the context of our project, a concave lens could be employed to widen the detection range of the IR sensors. For example, our proximity sensor might require coverage over a larger area to ensure accurate object detection, a concave lens can help spread the emitted LED light, enhancing the system's capability across a broader area around the enclosure. This ensures that the cat's presence is reliably detected without needing to reposition the sensors or compromise the system's precision.

Choosing the right lens requires careful consideration of several factors, starting with the desired level of magnification. We must also think about the shape of the lens, with Fresnel lenses providing a compact alternative to more traditional convex lenses. What about the wavelength of light we're using? If it's on the shorter or longer end of the optical spectrum, some lens materials are obviously going to work better than others. Sharp images and the correction of optical aberrations are key when what you're doing requires high precision. For our project, it's already decided that we're using LEDs on the infrared spectrum, so we will consider what works best for that range of the optical spectrum.

Another important consideration is cost. Some of the specialized lenses we might want to use are considerably more expensive than simpler, less capable options. And if we get into a large-scale production situation, the availability of the lenses we want will have to be reckoned with, too, especially given a manufacturing process we might want to prototype with first. For that reason, it might be smart to have a couple of different lens options available in our evaluation phase.

Plano-convex lenses are often the go-to choice. The flat side of these lenses is placed toward the light source, which allows them to focus accumulated light onto a detector. For a proximity sensor, that would be the photodiode, a lens design that increases the sensitivity and range of the sensor. If you want to get fancy, you can use an aspheric lens instead, which has less spherical aberration and thus provides better focus.

When an infrared application calls for a lens, the selection process demands the careful picking of certain materials known for having optimal infrared transmission qualities. Among the options available, germanium is commonly utilized in optics, while silicon serves as another viable material for fabricating top-notch infrared optical components. Coatings are frequently applied to lenses; however, when it comes to infrared applications, it's crucial to ensure that the coating suits the wavelength in question.

The proximity sensor's field of view is another aspect to consider. A lens with a shorter focal length provides a wide field of view; it would do well if the sensor needed to detect objects over a broad area. In contrast, a lens with a longer focal length gives a narrower field of view, but in this case, that's a good thing if the sensor is set up to detect objects at longer ranges, so a beam that's more focused, that is, a narrower field of view, is what's needed. A lens design that doesn't interfere optically, mechanically, or otherwise with the sensor or surrounding components is crucial.

3.1.7.3.1 Break-Beam Lens

Choosing a lens for a proximity sensor also works for a break beam sensor setup since both systems detect the interruption of light. The break beam sensor is also going to be made up of an IR LED and a light detector. The LED emits a beam that is directed toward the light detector, which in our project will also be photodiode. An object passing in front of the beam interrupts it, which triggers the light detector.

Using a convex or Fresnel lens in a break beam sensor arrangement can boost the focus and intensity of the IR beam. This arrangement becomes more reliable as the distances increase. An LED paired with a lens can project infrared light in

a more precise manner. The lens allows the LED to cast its light in a narrowly defined manner, rather than flooding the space in front of it with light. This arrangement makes it more likely that the detector and lens combination will sense when the beam path is broken.

The lens material is likewise fundamental to a break beam sensor. As with proximity sensors, the use of materials that are transparent to infrared light, such as silicon or germanium, can boost efficiency when the sensor. These materials let the infrared light pass through with low enough absorption that the light remains undiluted enough to power the sensor into a detection-ready state.

Finally, placing lenses in both proximity and break-beam sensors strengthens the system's performance because they focus the infrared light, which extends the range and improves the accuracy of detection.

3.1.7.3.2 Conclusion

Choosing to use the plano-concave lens for the proximity sensor and the plano-convex lens for the break beam sensor was a deliberate decision to elevate the effectiveness of both systems. The proximity sensor utilizes a plano-concave lens to widen its field of view, which helps it achieve better object detection. This design will help in efficiently dispensing the emitted infrared light, rendering it ideal for uses that require a larger detection area. Additionally, in the break beam sensor, the infrared beam is focused with precision onto the detector by using a plano-convex lens, producing a well-collimated directional beam. Concentrated light reduces divergence and enhances the precision of detection. In our case, it will be used to tell whether the cat has entered the litter box enclosure. In addition, the lens enhances the sensitivity of the photodiode in both subsystems.

The plano-concave lens helps to gather reflected light from a wider area for the proximity sensor, while the plano-convex lens focuses more of the light, in a narrower beam, for the break beam sensor. Choosing lenses to suit the precise requirements of each application helps the system as a whole achieve a state of balanced efficiency and reliability.

3.1.8 Voltage Regulation

Voltage regulators will help avoid inconsistencies in voltage which could cause our devices to malfunction or overheat. Maintaining a stable output voltage ensures the safe and efficient operation of our electronic components such as the motor, microcontroller, and sensors, regardless of variations in input voltage or load conditions. Voltage regulators serve two main functions: they adjust the input voltage to a specific output level, and they regulate the voltage to keep it

consistent despite changes in the load. Voltage regulation is integral to our power system, with DC-DC regulators being a key component. Choosing the correct regulator for our system is critical to ensure a reliable and efficient power supply.

There are two main types of voltage regulators: linear regulators and switching regulators. Linear regulators are considered inexpensive devices that drop excess voltage by converting it into heat, making them easy to implement but inefficient for high-power applications. Switching regulators, on the other hand, use more complex techniques to adjust the voltage with much higher efficiency. These regulators are particularly important in systems that require either stepping up or stepping down voltage.

3.1.8.1 Linear Voltage Regulators

Linear regulators are devices that use transistors to drop the input voltage to the desired output level. They are commonly used in low-power applications due to their simplicity and low cost, but they are inefficient when there is a large difference between input and output voltages, as the excess energy is dissipated as heat. This makes them unsuitable for high-power applications but useful for circuits where minimal noise and simplicity are essential.

3.1.8.1.1 Series Voltage Regulators

Series regulators are among the most commonly used linear regulators. They work by placing a variable resistance in the path of the input voltage, controlling the voltage drop to maintain a constant output. Low-Dropout (LDO) regulators, a common type of series regulator, can operate with a very small difference between the input and output voltage. This makes them highly efficient in low-power applications where minimal voltage loss is critical. However, they have the same downside as linear regulators, that they convert the excess input voltage into heat, which can make them less efficient when the difference between input and output voltage is large. The efficiency tends to decrease as the load current increases, making them less suitable for high-power applications where large amounts of energy would be wasted as heat.

3.1.8.1.2 Shunt Regulators

Shunt regulators, or parallel regulators, operate by diverting excess current away from the load to ground to maintain a stable output voltage. Unlike series regulators, they do not adjust the voltage drop across the load; instead, they continuously "shunt" the excess current to keep the output voltage constant. Shunt regulators are often simpler and cheaper to implement. However, they are typically less efficient than series regulators, especially when the input voltage is

much higher than the required output voltage, because they continue to draw current even when the load demand is low. This constant power draw makes shunt regulators inefficient in high-power or variable load systems, but they can be a good choice when simplicity and cost are more important than high efficiency.

3.1.8.2 Switching Voltage Regulators

Switching regulators offer a more efficient alternative by using high-speed switches to control the flow of power, allowing them to step-up or step-down voltage without generating excessive heat. They are highly efficient, especially in applications where large voltage differences exist between the input and output. There are three main types of switching regulators: buck, boost, and buck-boost regulators, each serving different purposes depending on the power needs of the system.

3.1.8.2.1 Buck Regulators

A buck regulator is designed to step down voltage, taking a higher input voltage and reducing it to a lower output voltage. Buck regulators are widely used in systems where voltage needs to be reduced from a bus voltage to the load, as they maintain high efficiency. They are ideal for applications where the power source provides more voltage than the system requires, making them one of the most commonly used regulators.

3.1.8.2.2 Boost Regulators

A boost regulator does the opposite of a buck regulator; it steps up voltage, increasing a lower input voltage to a higher output voltage. This is especially useful in applications where boosting the voltage can reduce power losses, such as long cable power transmission. Boost regulators also maintain high efficiency and are critical in situations where the power source provides lower voltage than needed.

3.1.8.2.3 Buck-Boost Regulators

A buck-boost regulator is versatile in that it can both step up or step down the input voltage depending on the system's needs. This makes it ideal for systems with variable input voltage, such as battery-powered devices, where the voltage may fluctuate as the battery charges or discharges. Buck-boost regulators can provide a stable output even when the input voltage swings above or below the desired output. However, due to the complexity of managing both step-up and

step-down functions, their efficiency is slightly lower than dedicated buck or boost converters.

Table (3.2) - Linear and switching regulators comparisons.

Aspect	Linear Regulators	Switching Regulators		
		Buck	Boost	Buck-Boost
Voltage Output	Step-Down	Step-Down	Step-Up	Step-up or Step-Down
Heat Dissipation (moderate load)	5-15W	1-5W	1.5-6W	2-8W
Efficiency	40-50%	85-95%	80-90%	75-90%
Cost	\$0.10 to \$2	\$0.50 to \$6	\$1 to \$8	\$2 to \$12

3.1.8.3 Conclusion

After analysis of the regulators, we concluded choosing a buck switching regulator would best fit our needs for power efficiency and cost in the final design. Ideally to ensure our components receive stable, regulated power, we would choose a 3.3V and 5V buck regulator which would step-down the converted AC-DC 12V power bus previously chosen as the initial power supply. We will go into more detail later breaking down which choice of buck switching regulator will best suit our needs. Overall, this regulator will be effective to efficiently step-down the voltage, minimize heat loss, and improve overall energy efficiency, which is crucial for long-term use of the system.

3.1.9 Embedded Communication Protocols

In embedded systems design, selecting the appropriate communication protocol between microcontrollers and other system components is crucial for ensuring reliable and efficient operation. This document examines four primary communication protocols commonly used in embedded systems: Universal Asynchronous Receiver Transmitter (UART), Inter-Integrated Circuit (I²C), Serial

Peripheral Interface (SPI), and Universal Serial Bus (USB). Additionally, it details the specific implementation of UART communication in our project.

3.1.9.1 Universal Asynchronous Receiver Transmitter (UART)

UART represents one of the oldest and most widely-implemented communication protocols in embedded systems. Its primary characteristic is the ability to transmit and receive data serially without requiring a clock signal for synchronization. Instead, UART relies on predetermined baud rates shared between communicating devices to ensure proper data transmission and reception.

UART communication is based on data frames that include a start bit (logic 0), followed by data bits (5-9 bits), an optional parity bit, and concluding with stop bit(s) (logic 1). This structure ensures reliable data transmission without clock synchronization.

3.1.9.1.1 Simplex Configuration

The simplex configuration represents the most basic implementation, utilizing a single data line for unidirectional communication. In this setup, the transmitting device cannot receive data, making it the simplest and most power-efficient configuration, though also the most limited in functionality.

3.1.9.1.2 Half-Duplex Configuration

Half-duplex configuration employs a single data line while enabling bidirectional communication. Devices can both transmit and receive data, though not simultaneously due to the single-line limitation. This configuration offers a moderate power consumption profile while providing more flexibility than simplex operation.

3.1.9.1.3 Full-Duplex Configuration

Full-duplex configuration utilizes two dedicated data lines (TX and RX), enabling simultaneous bidirectional communication. This setup eliminates the need for a master-slave hierarchy, though it comes with higher power consumption. The configuration provides maximum flexibility for complex communication needs.

3.1.9.1.4 Advantages

UART communication offers numerous benefits that make it an attractive choice for many applications. Its implementation is straightforward and requires no clock synchronization, while supporting direct device-to-device communication. The protocol accommodates variable data frame sizes and maintains low power

consumption requirements. UART's minimal pin requirements simplify hardware design, and its built-in error detection via parity checking adds reliability. The protocol enjoys widespread support across microcontrollers, and developers can access extensive debugging tools for troubleshooting and optimization.

3.1.9.1.5 Limitations

Despite its benefits, UART faces several notable limitations. Data transfer speeds are relatively slow, typically maxing out at 115.2 Kbps. The protocol's error detection capabilities are limited, and proper operation requires matching baud rates between communicating devices. UART lacks built-in flow control and is restricted to point-to-point communication. The protocol can be susceptible to timing errors, which may affect reliability in some applications.

3.1.9.2 Inter-Integrated Circuit (I²C)

I²C represents a more sophisticated protocol designed for short-distance communication between integrated circuits. It utilizes a two-wire interface for bi-directional communication.

The I²C protocol operates using two primary lines: the Serial Clock Line (SCL) for timing information and the Serial Data Line (SDA) for data transmission. The system employs an open-drain configuration with pull-up resistors and supports multiple masters and slaves. Addressing can be either 7-bit or 10-bit, with 7-bit addressing supporting up to 128 devices on a single bus.

I²C supports various speed modes to accommodate different application requirements. Standard Mode operates at 100 kbit/s, while Fast Mode achieves 400 kbit/s. Fast Mode Plus extends capabilities to 1 Mbit/s, and High Speed Mode reaches 3.4 Mbit/s. The Ultra Fast Mode pushes performance to 5 Mbit/s, though this mode has specific implementation requirements.

3.1.9.2.1 Advantages

I²C provides significant advantages through its efficient two-wire implementation that supports multiple slave devices. The protocol includes a built-in addressing system and offers flexible master-slave configuration options. Hardware flow control enhances reliability, and the standardized protocol ensures broad compatibility across devices and manufacturers.

3.1.9.2.2 Limitations

The protocol presents certain challenges, including greater complexity compared to UART and restrictions on cable length. Implementation requires pull-up

resistors, and while faster than UART, I²C operates at lower speeds than SPI. The addressing system of the protocol, while being powerful, introduces overhead that can impact system performance and responsiveness in some applications.

3.1.9.3 Serial Peripheral Interface (SPI)

SPI provides a full-duplex, synchronous serial communication protocol that offers higher speeds than both UART and I²C. It uses a master-slave architecture with dedicated lines for data and clock.

SPI operates using four main signals: MOSI (Master Out Slave In) for data output from master, MISO (Master In Slave Out) for data input to master, SCK (Serial Clock) for synchronization, and SS/CS (Slave Select/Chip Select) for device selection. This comprehensive signal structure enables efficient and reliable communication.

3.1.9.3.1 Advantages

SPI excels in several areas, providing the fastest communication speeds among the three serial protocols discussed. The protocol enables full-duplex communication without requiring device addressing, and its hardware implementation remains relatively simple. The absence of start/stop bits reduces overhead, while flexible data frame sizes accommodate various data types and structures.

3.1.9.3.2 Limitations

The protocol's primary drawbacks stem from its hardware requirements, needing more pins than either UART or I²C. SPI lacks built-in flow control and error checking mechanisms, potentially affecting reliability in some applications. The protocol's distance capabilities are limited, and it typically supports only one master device, though some implementations allow for multiple masters through additional complexity.

3.1.9.4 Universal Serial Bus (USB)

USB represents the most complex but versatile of the four protocols, offering high-speed data transfer and widespread compatibility with modern devices.

USB employs differential signaling through D+ and D- lines, supporting multiple speed grades while providing built-in power delivery capabilities. The protocol implements a complex stack that enables robust communication and device management.

USB's various speed grades accommodate diverse application requirements. Low Speed operates at 1.5 Mbit/s, while Full Speed achieves 12 Mbit/s. High Speed significantly increases throughput to 480 Mbit/s, and SuperSpeed reaches 5 Gbit/s. SuperSpeed+ further extends capabilities to 10-20 Gbit/s, though these higher speeds require specific hardware support.

3.1.9.4.1 Advantages

USB provides substantial benefits through its high data transfer rates and widespread compatibility with modern devices. The protocol's power delivery capabilities enhance flexibility, while hot-plug support simplifies device connection and disconnection. Robust error detection ensures reliable data transmission, making USB ideal for complex applications requiring high-speed, reliable communication.

3.1.9.4.2 Limitations

USB implementation presents several challenges, primarily due to its complexity and the requirement for specialized hardware. The protocol typically consumes more power than simpler alternatives and increases implementation costs. For basic applications, USB's sophisticated features may represent unnecessary overhead, making simpler protocols more appropriate.

3.1.9.5 Project Communication Requirements

The project requires communication between a Raspberry Pi (running AI-based image recognition) and an MSP430 microcontroller (handling sensor inputs and motor control). The communication needs encompass unidirectional data flow from the Raspberry Pi to MSP430, simple command structure, low power consumption, reliable operation, and cost-effective implementation.

3.1.9.6 Protocol Selection

For this project, UART was selected as the primary communication protocol between the Raspberry Pi and MSP430 for several key reasons. The protocol's straightforward implementation allows for quick development and debugging, while the simplex configuration's minimal hardware requirements result in lower power consumption. UART's speed capabilities adequately meet the relatively low data transfer requirements for simple door control commands. Both the Raspberry Pi and MSP430 feature built-in UART hardware, simplifying implementation, while the simplex configuration perfectly matches the project's one-way communication requirement.

The implementation utilizes a 9600 bps baud rate, which provides sufficient speed for command transmission. A simplex configuration enables one-way communication, while the data format employs 8 data bits without parity and one stop bit. The command structure relies on simple byte-based commands for door control and status monitoring.

3.1.9.7 Conclusion

While each communication protocol offers distinct advantages and limitations, UART's simplicity, low power consumption, and adequate speed make it the ideal choice for our project. The unidirectional communication requirement is perfectly served by UART's simplex configuration, while the built-in support on both the Raspberry Pi and MSP430 ensures straightforward implementation and reliable operation.

The project's success demonstrates that choosing the right communication protocol involves carefully considering not just technical capabilities, but also practical factors such as power consumption, implementation complexity, and specific application requirements. In this case, UART's simplicity and efficiency perfectly match the project's needs, allowing for reliable communication between the system's key components while maintaining low power consumption and implementation complexity.

3.2 Part Selection

This subsection discusses the specific parts selected as the core components of the project.

3.2.1 Single-Board Computer Part Options

For the P.A.W.S. project, the SBC will communicate with the microcontroller to handle most of the tasks. The MCU will control the door motor, the LCD panel, and wirelessly send data to the mobile app, allowing the SBC to focus exclusively on the machine learning tasks. Because this process takes a significant amount of computational power, it's crucial that the SBC can remain in a low-power idle mode in order to prevent excessive heat build up. Cost is another important consideration; while cheaper SBCs are available for as low as \$50, more expensive options can exceed \$500. Although processing speed is an important factor, P.A.W.S. does not require rapid object tracking or particularly quick detection times. Instead, it is more important for the model to be able to accurately identify the animal. For this project, the most important factors to consider should be the cost and computing power.

3.2.1.1 Raspberry Pi 4 Model B

The Raspberry Pi 4 is the fourth major development version of the Raspberry Pi single-board computer developed by Raspberry Pi Trading and released on June 24, 2019. This option is likely the most popular and widely used SBC because of its relatively low cost, high availability, and ease of use for beginners and experts alike. Because of the board's popularity, the Pi 4 has extensive documentation and tutorials that make it suitable for a student project like P.A.W.S. The specific model that is presented as a possible option for the project is the Raspberry Pi 4 Model B.

Specs-wise, the Model B comes equipped with a quad core 1.8 GHz 64-bit Cortex-A72 SoC (system-on-chip) processor. Although the Pi 4 does have 2.4 GHz and 5.0 GHz IEEE 802.11ac wireless and Bluetooth 5.0 capabilities, these factors are not important considerations as the microcontroller will be the part that communicates wirelessly with the integrated mobile app. It also has 2 USB 3.0 ports, 2 USB 2.0 ports, 2 micro-HDMI ports, a 2-lane MIPI DSI display port, a 2-lane MIPI CSI camera port, and a 4-pole stereo audio and composite video port. The chosen Raspberry Pi Camera Module 3 part will be able to connect directly to the Pi 4 through these ports. As the camera is also made by the Raspberry Pi company, it is perfectly compatible with any version of the Pi 4. The Pi 4 is able to decode and display up to 4kp 60fps video with the H.265 HEVC (high efficiency video coding) standard. With H264, it can decode up to 1080p60 or encode up to 1080p30. Although it can reach up to these video qualities, the P.A.W.S. project will never feasibly reach them due to the majority of the processing power of the Pi 4 going towards the AI processing. The Pi 4 by itself requires a 5 Volt, 3 Amp power adapter. However, the work required for the P.A.W.S. project is unlikely to reach anywhere near the highest power consumption. In idle state, the Pi 4 will typically consume around 1.02 Watts, and during a stress test will consume up to 6.2 Watts. The Pi 4 does not have a true sleep mode, but its power consumption can still be reduced through shutdowns of unused modules. This makes the Pi 4 a suitable option when considering the project's heat regulation.

Despite the name, the Pi 4 line does not have a Model A version. Instead, the various options of the Pi 4 Model B are the differing amounts of RAM capacity. The Pi 4 Model B is sold in four versions, each with a different amount of LPDDR4 3200 MHz SDRAM: a 1GB, 2GB, 4GB, and 8GB version. If this product is chosen, then the RAM capacity is an important factor to consider for the project, as the memory plays a direct role in the board's AI object detection and classification speed. Depending on the 1, 2, 4, or 8 GB selected version, the price of the SBC is currently \$35, \$45, \$55, or \$75, respectively.

3.2.1.2 Raspberry Pi 5

The Raspberry Pi 5, released in October 2023, is the fifth major development version of the Raspberry Pi line of SBC products, and the direct successor to the Raspberry Pi 4. Similarly to its predecessor, the Pi 5 is a fairly popular SBC for small home developers, and thus also has extensive documentation and support. While this version of the Pi also comes in differing versions of RAM capacity, it does not have multiple model versions and is instead consolidated into just the Raspberry Pi 5.

For the specs, the Raspberry Pi 5 has an upgraded CPU of a quad core 2.4 GHz 64-bit Arm Cortex-A76, with cryptography extensions, 512KB per-core L2 caches, and a 2MB shared L3 cache. It has an integrated VideoCore VII GPU, with 12 cores and up to 800 MHz frequencies, that can support OpenGL ES 3.1 and Vulkan 1.2. Similarly to the Pi 4, this model also has dual-band 802.11ac Wi-Fi and Bluetooth 5.0 support. Again, however, these specs are not particularly important for the P.A.W.S. project specifically but are nice bonus features. The Pi 5 has the same 2 USB 3.0 ports and 2 USB 2.0 ports, but now also includes dual 4kp60 HDMI display output. It also includes the same 4kp60 HEVC decoder that the Pi 4 had. To connect with the Raspberry Pi Camera Module 3, the Pi 5 has 2 4-lane MIPI camera/display transceivers. If our team needs to connect any other peripherals, this version of the Pi now has a PCIe 2.0 interface. Finally, the power consumption is still a primary concern in the part selection process. The Raspberry Pi 5 has a higher potential power draw than its predecessor, requiring a 5 Volt, 5 Amp power adapter rather than the previous 5 Volt, 3 Amp adapter of the Pi 4. At idle, the Pi 5 consumes around 2.7 Watts, and during stress can consume up to 7 Watts. Although the stress test is only about 0.8 Watts higher than the Pi 4, the idle test sits at more than double the consumption. During stress testing, it was also found that the Raspberry Pi 5 would quickly start to thermal throttle when reaching temperatures of about 82 degrees Celsius. This led to a throttling of the CPU from 2.4 GHz down to 1.5 GHz frequencies. Luckily, the Raspberry Pi company sells an official Raspberry Pi Active Cooler module for only \$6.45. This module connects directly to the Pi 5, lowering both temperature and power consumption.

Similarly to the previous model, the Raspberry Pi 5 is sold in multiple versions that differ primarily on RAM capacity. This model is sold in 2GB, 4GB, and 8GB versions with LPDDR4X 4267 MHz SDRAM for \$50, \$60, and \$80 respectively. Because of the higher price tag for both the Pi and the cooler, the choice between the Pi 4 or the Pi 5 mainly comes down to how much processing power is actually needed for the AI portion of the project.

3.2.1.3 NVIDIA Jetson Nano

The NVIDIA Jetson Nano is a small form-factor SBC released by NVIDIA in March 2019. Although it's a fairly older board, the Jetson Nano was designed specifically for developers working with AI technology. NVIDIA currently remains one of the world's leading companies in AI innovation. Because of this, the Jetson Nano has extensive official documentation from NVIDIA on working with the product. Additionally, the Nano is also another fairly popular SBC for home projects, and thus also has impressive unofficial support from the community.

The major defining factor that makes the Jetson Nano special among the other SBC options is the inclusion of a 128-core NVIDIA Maxwell architecture GPU with a max frequency of 921 MHz. The GPU acts as a machine learning accelerator, allowing the Nano to train and run multiple AI workloads and neural networks at the same time. The inclusion of an integrated dedicated GPU makes the Jetson Nano by far the most powerful SBC on this list with regards to its performance on AI related tasks.

Some other important specs to consider are the quad core 1.43 GHz ARM Cortex-A57 MPCore processor, and optional 2GB or 4GB of 64-bit LPDDR4 RAM. The Jetson Nano is able to support up to four cameras at once with its 12-lane MIPI CSI-2 interface. However, our current camera selection of the Raspberry Pi Camera Module 3 would need to be replaced, as the two are incompatible. It can encode and decode video in H.265 standard up to 4kp30 and 4kp60 respectively. Similarly to the Raspberry Pi, the Jetson Nano has a PCIe Gen2 slot for peripherals, and four USB ports; these include 1 USB 3.0 and 3 USB 2.0 ports. For connecting with an external display, the Nano has 2 multi-mode display slots for DP 1.2, eDP 1.4, or HDMI 2.0. As a result of the extra power that comes with this SBC, the power draw is similarly increased over the previous options. On NVIDIA's specs page, it is noted that the Jetson Nano's power consumption at idle is about 5 Watts, whereas under stress it can consume as much as 10 Watts. The board does have an integrated active cooler, so heat can be managed even under stress.

The NVIDIA Jetson Nano has actually reached end-of-life status and ceased production as of March 2022. It was directly replaced by its successor, the Jetson Orin Nano, one year later. The Orin Nano has never been under consideration for this project, however, due to its incredibly expensive price of \$499. As previously mentioned, the Nano used to be sold in 2GB or 4GB RAM versions for \$59 and \$99. Currently, the only available options for purchasing the Nano are either through backlogged stock from third-party retailers, or by purchasing a used version through resellers on sites such as eBay. A typical third-party retailer

seems to sell Nanos for roughly \$150 to \$200, whereas reseller pages are currently selling used boards for about \$105 to \$130.

3.2.1.4 Coral Dev Board

Coral is a local AI focused branch of Google that includes years of collaborative work between the company's many AI focused divisions, such as Cloud and TensorFlow. The Coral Dev Board is the result of these collaborations. The first version of the board was released in March 2019, and has since seen multiple new versions to fit a wide range of use cases. Similarly to the Jetson Nano, the Coral Dev Board is an SBC that was designed from the beginning to be used primarily with AI related technology and tasks. Being a Google product, the Coral board has extensive official documentation. Unfortunately, it is a less popular option than the previous ones above, and so unofficial community support is more lacking. There are currently three different versions of the Coral Dev Board, each with different specs and varying use cases.

The full-size Coral Dev Board uses an integrated GC7000 Lite GPU and has an included machine learning accelerator. The onboard Google Edge TPU coprocessor is capable of performing up to 4 trillion operations per second, which can, along with the integrated GPU, massively increase the P.A.W.S. AI detection and classification speed. This version of Coral is equipped with an NXP i.MX 8M SoC (quad Cortex-A53, Cortex-M4F) processor. It has Wi-Fi 802.11b and Bluetooth 4.2 capabilities. For ports, it comes with connections for USB Type-C power, a USB 3.0 port, 3.5mm audio jack, HDMI 2.0 port, and 24-pin FFC connector for a camera. The board is powered through the USB Type-C port and requires a 5 Volt DC connection. The full-size Coral was originally sold in either 1GB or 4GB LPDDR4 RAM versions, however only the 1GB is currently available for \$129.99.

The Coral Dev Board Mini is a less powerful version of the full-size Dev Board released in October 2020. This version uses the same Edge TPU coprocessor as the first version, but the rest of the specs are generally less powerful. It is equipped with a MediaTek 8167s SoC (Quad-core Arm Cortex-A35) processor and 2GB LPDDR3 RAM. It actually has better wireless capabilities, with Wi-Fi 5 802.11a and Bluetooth 5.0. It still has the 3.5mm audio jack and 24-pin FFC connector for the camera, but only has two USB Type-C connection ports. The Dev Board Mini is only sold in one version for \$99.99.

The final version is the Dev Board Micro. This is the cheapest and least powerful model, coming in at \$79.99. The Micro is not under consideration for part selection, however, as it is not powerful enough to handle the machine learning tasks required for the P.A.W.S. project. It has the same ML accelerator as the

previous versions, but does not have an integrated GPU, and only has a 64MB RAM option. The Micro is only meant for small low-power embedded projects and prototypes.

3.2.1.5 BeagleBone Black

The BeagleBoard Foundation is a US-based non-profit corporation that provides a hub for developers to discuss designs and uses of BeagleBoard open-source software and hardware. All BeagleBoard board designs and components are completely open source and available for any users to freely manufacture themselves. Being a non-profit, BeagleBoard does not directly sell any products, but instead licenses out the brand name to third-party manufacturers such as Digi-Key. The corporation is fully funded by these royalty payments and donations. Because all of the products are completely open sourced, any BeagleBone boards have extensive user-created documentation and examples. The website also provides an open forum and Discord where users can discuss problems and solutions.

The specific BeagleBone board in consideration for this project is the BeagleBone Black. This is by far the oldest board in part selection, released back in April 2013. Despite this, it remains a relevant board with enough power to handle P.A.W.S. AI tasks. There are newer, more powerful boards available, however the Black is one of the cheaper and more cost-effective options, currently available for about \$53.62.

Being an older board, the specs aren't incredibly impressive by today's standards and in comparison with the other boards on this list. It features a 1 GHz ARM Cortex-A8 processor and only 512MB DDR3 800 MHz SDRAM. The board is powered with a miniUSB or DC jack, requiring a 5 Volt DC connection. Under stress, the BeagleBone Black will typically consume between 6 Watts to 10 Watts, roughly similar to the Raspberry Pi options. Although the board has no wireless capability, the P.A.W.S. project does not require it on the SBC, so this exclusion is fine. It has two USB 2.0 ports and interfaces for connecting with HDMI D type and LCD screens. Overall, the BeagleBone Black is one of the weaker options powerwise on this list, but remains an interesting choice due to the extensive community support and relatively cheaper cost.

3.2.1.6 Single-Board Computer Part Comparison and Selection

Before comparing SBC parts directly in a table, a couple of the options can be eliminated early.

The NVIDIA Jetson Nano is not in consideration for final part selection purely because of cost reasons. The part is not in full production from NVIDIA anymore as of 2022, with its successor the Jetson Orin being sold at a very steep \$499. As a result, the Nano requires a minimum budget of at least \$105 for a used board from a third-party reseller. Despite its processing power, great documentation, and specialized GPU, the Jetson will not be used for this project.

For a similar reason, the full-size Coral Dev Board is also not under consideration for selection. Although having both an integrated GPU and TPU coprocessor is extremely enticing for an AI focused project, it costs a minimum of \$129.99 and has lacking community support compared to the other options. There also exists a smaller Coral USB product that could be connected to a Raspberry Pi or the BeagleBone, however this part was never under consideration. Any of the SBCs listed will be able to handle the AI tasks without the added expense of an external TPU.

The P.A.W.S. project does not necessarily require the huge amount of processing power that the Coral Dev Board and NVIDIA Jetson Nano would provide. The cheaper, more efficient options like the Raspberry Pi models or the BeagleBone are easily powerful enough to handle the AI object detection and classification tasks. P.A.W.S. does not require particularly fast detection but does need accurate classification. While all specs will be compared, the most important to consider remain the cost, computing power, and RAM capacity.

Table (3.3) - Single-board computer component comparisons.

Component	Raspberry Pi 4	Raspberry Pi 5	Coral Dev Board Mini	BeagleBone Black
CPU	Quad-core ARM Cortex-A72	Quad-core ARM Cortex-A76	Quad-core ARM Cortex-A35	ARM Cortex-A8
CPU Clock Frequency	1.8 GHz	2.4 GHz	1.5 GHz	1 GHz
GPU	VideoCore VI	VideoCore VII	PowerVR GE8300	SGX530 3D Graphics Engine

RAM	1GB/2GB/4GB/8GB LPDDR4	2GB/4GB/8GB LPDDR4x	2GB LPDDR3	512MB DDR3
RAM Clock Speed	3200 MHz	4267 MHz	1600 MHz	800 MHz
Storage	microSD, USB 2.0/3.0	microSD, USB 2.0/3.0	8GB eMMC, microSD	4GB eMMC, microSD
I/O Ports	GPIO, I2C, SPI, UART	GPIO, I2C, SPI, UART	GPIO, I2C, SPI, UART	GPIO, I2C, SPI, UART
Networking	GB Ethernet, Wi-Fi, Bluetooth	GB Ethernet, Wi-Fi, Bluetooth	Wi-Fi, Bluetooth	Ethernet
Power Consumption	5V, 3A	5V, 5A	3.3V, 3A	5V, 2A
Approx. Cost	\$35.00 - \$75.00	\$50.00 - \$80.00	\$99.99	\$53.62

After directly comparing the four main SBC part selections in the table above, two choices can be easily eliminated. Although the BeagleBone Black has excellent community support due to its open-source nature, its age has unfortunately caught up with it. It is currently being sold for slightly more than the low-end Raspberry Pi 5, yet has significantly worse specifications than any of the other three choices in every regard except for power consumption. While power use is an important deciding factor, the cost efficiency and low processing specs unfortunately offset the slightly lower power draw, and so the BeagleBone Black is no longer under consideration.

The other easily eliminated SBC is the Coral Dev Board Mini. What was said for the BeagleBone Black can also be said for the Dev Board Mini. Despite being a much newer board from 2020, it is generally weaker than even the older Raspberry Pi 4 and at a significantly higher cost than any other board. The power draw is among the lowest of the choices and it does have an integrated ML TPU coprocessing accelerator. However, the P.A.W.S. project does not have a need

for the incredibly fast object detection speed that an accelerator would provide. The primary deciding factors for eliminating the Coral Dev Board Mini are its high price of at least \$99.99, low market availability, and niche community support.

After eliminating the BeagleBone Black and Coral Dev Board Mini, the remaining options are the Raspberry Pi 4 Model B and the Raspberry Pi 5. Among these models, it also needs to be determined as to which RAM version specifically to purchase for the project. Being the newer successor board, the Pi 5 is across the board more powerful than the Pi 4. This does come with the tradeoff of slightly higher pricing and a fairly significantly higher power draw and stress temperature. After considering research on methods to power the enclosure, we ended up deciding to use AC power connected through a wall plug. This means that power draw is of little consideration in the final decision. For temperature, the Pi 4 and Pi 5 both have compatible extra active cooling solutions, so this drawback is also fairly negated. This leaves the main consideration to be the overall cost, where the Pi 5 is roughly only a \$5 increase over the Pi 4 for the same RAM version. The group has decided that the P.A.W.S. enclosure will use the Raspberry Pi 5 4GB RAM version as it is the best option in terms of both computing power and cost efficiency.

3.2.2 Optical Parts Selection

This subsection discusses the optical components comprising the optics subsystem of the project.

3.2.2.1 Emitter Selection

This subsection discusses the emitter selection of the optics subsystem.

3.2.2.1.1 Vishay VLM-850-04-01

The Vishay VLM-850-04-01 is an ideal choice for proximity sensor designs that need low power. With about 100 mW power consumption, it is excellent for applications where object detection is needed. This infrared laser diode with an 850 nm wavelength has plenty of power for good efficiency in sensor designs, which is augmented by it using a plastic package that is slightly smaller than comparable devices and has an integrated lens. In fact, this is probably the most space-efficient alternative for a low-power IR proximity sensor design that requires visual detection of an object with a significant amount of infrared reflectance at a distance that can range from 1 to 30 meters[16].

3.2.2.1.2 Adafruit Super-bright IR LED ADA388

The ADA388 is a compact, efficient infrared laser diode module that works at 940 nm, and is often employed in tasks such as sensing proximity, detecting motion, and identifying objects. The 940 nm wavelength is favored for these applications because it significantly diminishes any interference from ambient light sources, including sunlight. This boosts the module's reliability in outdoor or well lit conditions but also makes it particularly suited for proximity sensors that need to perform consistently across a wide range of lighting environments. Additionally, the ADA388 is designed for low-power operation, making it an ideal candidate for use in portable, battery-powered, or other energy-efficient devices.

A main asset of the ADA388 is its small package, which makes it easy to fit into constricted designs. Adding to that, it's not overly complicated to make work, needing only the most basic of external circuitry to do the job, which helps reduce the overall sensor's part count and footprint. In contrast, the 940 nm wavelength does offer some resistance to interference from ambient light and can be less effective over long distances in high-sensitivity applications[17].

3.2.2.1.3 HiLetgo 5mm 940nm LEDs

The HiLetgo infrared emitter and receiver diode pack is a practical, affordable solution for building proximity sensors, motion detectors, or object detection systems. The IR LEDs and the infrared receiver in this pack operate at a wavelength of 940 nm. This makes them well-suited for installations where interference from ambient light must be kept to a minimum. Indoor and outdoor installations of motion detectors using this pack are practical and reliable.

The simple design of this product allows for seamless integration. It comes in a standard 5 mm package, making it compatible with a vast assortment of circuit types. This diode is perfect for any paired application in a custom sensor design. A single pack has enough components for an ample number of prototypes, or to finish up a small-scale project.

In contrast to more sophisticated infrared components, the 940nm LEDs don't have quite the range or sensitivity, especially in low-power applications that require longer detection distances. And if application demands involve speed or the sort of precision seen in high-end infrared tracking, these diodes aren't going to get the job done. All that said, the HiLetgo 5mm IR emitter and receiver pair is a solid, dependable choice for basic proximity applications and are budget friendly[18].

3.2.2.1.4 Conclusion

I selected the Adafruit Super-bright IR LED ADA388 instead of the Vishay VLM-850-04-01 and HiLetgo 5mm 940nm LEDs for several reasons. Through some preliminary tests done with a simple circuit, we learned how essential a detectable and strong IR signal is when working with photodiode sensors. One of the primary ways to achieve that is to increase the output power of the IR LED being used so that the effective IR signal is stronger. Proximity sensors and break beam systems need consistent IR illumination to work correctly, and the ADA388 is a good option for these applications. On top of that, Adafruit products are generally very well made and easy to work with, which is a great bonus when using them in any project situation.

Table (3.4) - IR Emitter Comparison table for proximity sensor and break-beam sensor

Component	Vishay VLM-850-04-01	Adafruit Super-bright IR LED ADA388	HiLetgo IR Emitter and Receiver LED pair
Wavelength	850 nm	940 nm	940 nm
Power Consumption	~ 100 mW	~ 30mW	~ 70mW
Operating Voltage	2.6 – 6 V	1.6 - 4 V	1.2 – 3.5
Operating Current	< 40mA	< 20mA	< 20mA
Beam Divergence (Half-Angle)	< 1 deg	10 deg	10 deg
Weight	-	0.32 ounces	-

Dimension	10.5 mm x 19 mm 5mm diameter	35mm x 5mm 5 mm diameter	35 mm x 5 mm 5mm diameter
Range	1~30 meters	-	-
Approx. Cost (per unit)	~ \$30	~\$0.45	~\$0.27

3.2.2.2 Receiver Selection

This subsection discusses the receiver selection of the optics subsystem.

3.2.2.2.1 Adafruit TSOP38238

The TSOP38238 infrared receiver sensor is a reliable, low-cost infrared sensor widely used in many markets. The TSOP38238 will respond best when the incident infrared light is modulated at 38 kHz. However, it works very well as a general-purpose IR sensor, demodulating and detecting pulsed infrared light. This gives it a lot of versatility. Proximity sensors, beam break sensors, and remote controls are three applications in which you might find the TSOP38238.

The TSOP38238 is compact, has a simple three-pin interface, and is thus, very easy to integrate into any kind of circuit, including those built around the Arduino or Raspberry Pi series of microcontrollers. The sensor is designed to have a very fast response to the IR light signals it receives. The range of the TSOP38238, as with any other IR receiver, depends on the power given by the IR emitter. A typical range for the TSOP38238 operating with a common IR LED is 2–3 m.

The TSOP38238 might work well for our project because it provides high accuracy and aid against interfering ambient infrared light in real-world settings filled with a variety of infrared sources. These are rooms in which people are using a variety of infrared-emitting devices, for example. Moreover, the sensor is designed to detect only a specific pulse frequency, 38 kHz, that can just as easily be generated with a simple modulated circuit and LEDs[19].

3.2.2.2.2 BPW34 by Digikey

The IR photodiode BPW34 from Vishay is a versatile and highly sensitive detector. It is widely used for infrared light detection in several applications, like the following: proximity sensors, break-beam sensors, and ambient light monitoring. The BPW34 operates within the infrared spectrum, peaking at around 950nm. The standard IR LED emitters align with this range. Thanks to a combination of low dark current and a favorable response time, the BPW34 is especially suited for projects where precision, speed, and low noise matter.

The BPW34 has distinct advantages in that it can provide high sensitivity in a package that is small and inexpensive. While many IR modules tend to require a specific modulation frequency, this photodiode makes no such demands and can work well with any IR emitter module.

The BPW34 could be an excellent fit for our project since it offers simple IR detection and is a breeze to work with when setting up proximity sensors or break beam detectors. We could easily pair it with an IR LED to create a very basic IR detection system. This is a viable option for our project, it will meet our needs while also being cost effective[20].

Table (3.5) - IR Receiver Comparison table for proximity sensor and break-beam sensor

Component	Adafruit TSOP38238	BPW34 by Digikey	HiLetgo IR Emitter and Receiver LED pair
Wavelength	950 nm	950 nm	940 nm
Power Consumption	10 mW	215mW	70mW
Operating Voltage	2.5 - 5.5 V	5-10 V	1.2 – 3.5 V

Operating Current	3 mA	40 mA	20 mA
Beam Divergence (Half-Angle)	45 °	65 °	10 °
Weight	0.43g	-	-
Dimension	5.20mm x 6.98mm x 7.86mm	5.4 mm x 4.3 mm x 3.2 mm	35 mm x 5 mm 5mm dia.
Approx. Cost (per unit)	~ \$1.95	~ \$1.39	~ \$0.27

3.2.2.2.3 Conclusion

We selected the HiLetgo IR Receiver LED for our project, rather than the TSOP38238 IR Receiver Sensor, which is designed to receive and decode modulated IR signals, or the BPW34 photodiode. The HiLetgo LED is simple and straightforward to use; by pairing it with the Super-bright IR LED we were able to have a simple setup working perfectly for our project needs. We didn't require any modulation to get it working, this simplifies the complexity of circuitry design greatly, ensuring we are able to meet our goals more efficiently.

3.2.3 Motor Options

Given the project's requirements and constraints, the focus is narrowed to stepper motors. The following subsection details and compares several different motor options currently available on the market.

3.2.3.1 Motor Part Comparison and Selection

For the project's motorized linear rail system, several different NEMA 17 and NEMA 23 models are compared. The first (and most obvious) parameter taken into consideration when comparing is the load consideration. The load being driven by the motor consists of a threaded rod and plexiglass sheet. A NEMA 17

motor will likely provide sufficient torque, while a NEMA 23 will definitely do so. However, NEMA 17 motors offer advantages in terms of cost and power efficiency. They are cheaper than NEMA 23 and typically operate at lower temperature under moderate loads. Not only that, but the widespread adoption of NEMA 17 motors (in consumer-grade 3D printers, automation, etc.) has also led to the creation of a plethora of compatible controllers, drivers, and mounting solutions at very budget-friendly prices. So even though NEMA 23 motors can also be found to be compatible with common stepper drivers like the A4988 and DRV8825, they usually require higher-current drivers and more substantial power supplies. Additionally, factors such as rapid-change acceleration, micro-stepping capabilities needed for smooth operation, and the overall duty cycle of the application – all technological advancements provided by the NEMA 23 over the NEMA 17 – are not priority to the project, as the linear rail system is relatively simple and speed is the main concern. So while the NEMA 23 models provide higher torque, that level of torque is excessive for this application and would increase both cost and power consumption overall.

Table (3.6) - Stepper motor comparisons.

Product Specifications	Stepper Motors					
Manufacturer	STEPPER ONLINE	CNCTOP BAOS	STEPPER ONLINE	JOYNANO	STEPPER ONLINE	RATTMMOTOR
Model	Nema 17	Nema 17	Nema 17	Nema 17	Nema 23	NEMA 23
Price	\$11.99	\$12.50	\$13.99	\$15.99	\$29.99	\$30.00
Manufacturer Part Number	17HS15-1504S-X1	17HS8401	17HS19-2004S1	M42SH48-1684A	23HS30-2804S	23HS9430
Magnet Mechanism	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid

Wire Configuration	Bipolar	Bipolar	Bipolar	Bipolar	Bipolar	Bipolar
Step Angle	1.8°	1.8°	1.8°	1.8°	1.8°	1.8°
Holding Torque	45 N-cm	52 N-cm	59 N-cm	59 N-cm	190 N-cm	210 N-cm
Rated Current/Phase	1.50A	1.8A	2.0A	1.68A	2.8A	3.0A
Phase Resistance	2.3Ω	1.8Ω	1.4Ω	1.65Ω	1.13Ω	0.75Ω
Phase Inductance	4.4mH ± 20% (1Khz)	3.2mH ± 20%(1KHz)	3.0mH ± 20% (1Khz)	2.8mH ± 20%	5.4mH ± 20%(1KHz)	4mH ± 20%
Driving Voltage	12-24V	3.0V	12-24V	12V-24V	3.2V	20V
Number of Leads	4	4	4	4	4	4
Dimensions (L x W x H)	4.45" x 2.95" x 2.72"	1.65" x 1.65" x 1.89"	1.65" x 1.65" x 1.89"	1.65" x 1.65" x 1.85"	2.24" x 2.24" x 3.0"	3.19" x 1.85" x 2.21"

With these considerations, all NEMA 23 motor models can be ruled out. The next stepper motor model to be ruled out is the CNCTOPBAOS 17HS8401 model. This is because its driving voltage is 3V. This would require Integrating another regulator into the project's power design, overall increasing the complexity of the system.

The remaining NEMA 17 stepper motor options in the table now have the same voltage rating. The main specifications we're looking for in the chosen motor are high torque, low current draw, and low inductance. The STEPPERONLINE 17HS19-2004S1 model and JOYNANO M42SH48-1684A model both offer the highest holding torque within the NEMA 17 motor options. At 59 N-cm, this is more than sufficient for the rail system and will ensure that the motor can handle the weight and resistance associated with our linear motion of the plexiglass door across the rod.

Next, the JOYNANO model's rated current per phase is 1.68A, which is below the STEPPERONLINE model's 2.0A exhibiting the same torque specifications. This

means we can get a lower current draw but more efficient use of the motor. Additionally, the phase inductance of the JOYNANO model is lower than both remaining STEPPERONLINE models. With a 2.8mH inductance compared to their 4.4mH and 3.0mH inductances, we are benefited by faster current changes, resulting in quicker and more precise movements. This is ideal for maintaining a responsive and smooth motion on our linear rail system. These are important factors for an automated access system, as a faster response enables prompt access to the litterbox and overall increased usability for pets.

Lastly, the JOYNANO model is priced at \$15.99. Although this is higher than both the STEPPERONLINE model prices, it's a cost-effective choice in the long run because it offers excellent performance with only a few extra dollars. So when combined with JOYNANO's other benefits, this small price increase of the JOYNANO model becomes negligible.

With these last considerations, the JOYNANO NEMA 17 emerges as the optimal choice for the project's linear rail system, meeting all key criteria.

3.2.4 Display Part Options

For the P.A.W.S. project, a TFT LCD with IPS technology was selected as the primary interface, connecting to the Raspberry Pi SBC to facilitate user interaction. This LCD will allow users to operate the enclosure and interact with the project's mobile application component. This subsection outlines the selection criteria for the display, followed by a comparison of various model options to identify the best fit for the project.

3.2.4.1 LCD Selection Criteria

The LCD's primary purpose is to maximize user engagement and satisfaction by providing a straightforward graphical interface. Achieving this goal requires careful attention to several important factors, beginning with screen size. The display must be large enough for comfortable interaction but not so large that it disrupts the enclosure's design. A screen that is too small could hinder usability, making interface elements difficult to see or touch. Conversely, an oversized screen could crowd the enclosure, complicate the physical layout, and create an imbalanced appearance. A 5-inch screen size offers a good starting point for screen size, delivering sufficient space for displaying graphics and text without overwhelming the enclosure.

Resolution is another crucial consideration. While it should be high enough to display graphics and text with clarity, anything beyond HD quality would be excessive for the needs of this project. A resolution of around 800x480 pixels will

provide sharp enough visuals and aid in color contrast, enhancing user experience without incurring the additional costs associated with ultra-high-definition displays. This balance ensures that the screen can deliver clear, color-accurate images suited to the project specifications.

The LCD's voltage rating must also align with the project's power setup. Since the project is powered by a 12V source, the LCD must operate within this limit. This eliminates the need for additional voltage regulation components, and not only simplifies power delivery but also reduces the risk of power-related issues. This overall promotes a more straightforward and reliable design.

Finally, cost is an essential factor. While optimizing for screen size and resolution, it's important to stay within budget constraints. Larger screens and higher resolutions will naturally drive up the project's expenses, so a careful balance must be struck between these features and overall cost-effectiveness. By selecting a display that meets all functional requirements without exceeding budget limits, we can maximize the value while ensuring a functional and user-friendly interface.

3.2.4.2 LCD Part Comparison and Selection

The team decided that the minimum screen size for the project's LCD needs is 5 inches. This means all model options considered and compared in the table below feature screen sizes of 5 inches or more. All the LCD models also have a relatively high refresh rate of 60 Hz as well as resolution of 800x480 pixels or above. Moreover, all exhibit a wide viewing angle of 160 degrees or more. These parameters are more than sufficient for our project needs. Additionally, the majority of the LCD model options below show capacitive touch capabilities.

Table (3.7) - LCD screen comparisons.

Product Specifications	Raspberry Pi Touchscreen LCD				
Manufacturer	ELECROW	FREENOVE	iPistBit	Hosyond	Hosyond
Price	\$38.99	\$39.95	\$39.59	\$32.99	\$45.99
Screen size	5"	5"	5"	5"	7"
Screen Technology	TFT	IPS	IPS	IPS	IPS
Resolution	800 x 480 px	800 x 480 px	800 x 480 px	800 x 480 px	1024 x 600 px (up to 1920x1080)
LCD Active Area	4.79" x 3.07"	8.35" x 5.51"	4.72" x 2.95"	4.25" x 2.55"	6.5" x 5"
Touch Screen Type	Resistive	Capacitive	Capacitive	Capacitive	Capacitive
Refresh Rate	60 Hz	60 Hz	60 Hz	60 Hz	60 Hz
Aspect Ratio	16:9	16:9	5:3	5:3	16:9
Viewing Angle	170°	160°	178°	178°	178°
Hardware Interface	Mini HDMI (1), HDMI (1)	MIPI DSI (1)	MIPI DSI (1)	MIPI DSI (1)	HDMI (1)
Voltage Rating	5V	3V	N/A	3.3V	5V

This leads us to the first model that can be eliminated: the ELECROW 5" LCD. It features a resistive touchscreen. Unlike capacitive touchscreens, resistive screens rely on pressure, making them less responsive and precise. This limitation makes it less suitable for our project.

The next model to eliminate is the Hosyond 7" LCD, primarily due to its high cost. As the most expensive option, it doesn't offer significant advantages for our project, where screen size beyond 5 inches and resolution above 800 x 480 pixels

are not priority parameters. The added expense doesn't justify the minimal benefit, making it an inefficient choice for our needs.

Of the remaining three 5" LCD model options on the table, the FREENOVE model stands out with its 16:9 aspect ratio. While the iPistBit and Hosyond models both have a 5:3 aspect ratio and this would be reasonable for the project needs, the 16:9 format is the industry standard for widescreen displays and is better suited to a wide range of applications. From video content to modern interfaces, it is more versatile and compatible with the majority of UI designs, which are typically optimized for 16:9. In addition, the 16:9 aspect ratio offers a more immersive viewing experience by maximizing screen width, making it ideal for applications that benefit from a wider field of view.

This advantage, along with FREENOVE's comparable specifications, positions it as the top pick for the project. Its widescreen format will enhance usability -- providing a more refined, modern display experience-- while fitting the cost, screen size, and resolution specifications.

3.2.5 Voltage Buck Converter Options

For our P.A.W.S. system, implementing voltage regulation is critical to efficiently power various components with different voltage requirements. The main power source will provide a stable 12V bus, which needs to be stepped down to both 5V and 3.3V to accommodate certain elements. High-current devices, like stepper motors and the control systems for actuating the door, require a regulated 5V supply to ensure reliable operation, especially under load conditions. Additionally, sensors, microcontrollers, and other low-power peripherals will operate at 3.3V and below. Given the significant current draw from high-power devices like motors, we will have a dedicated step-down voltage regulator to handle these demands, as well as a separate regulator for the low-power components to optimize power distribution. This approach will ensure that each subsystem receives stable power, enhancing our overall performance and reliability of the system. The following table compares 3 voltage regulators we initially considered:

Table (3.8) - Voltage Buck Converter comparisons.

	Voltage Buck Converters
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Aspect	LM2596	TPS54JA20	MP2315
Brand	Texas Instruments	Texas Instruments	Monolithic Power Systems
Input Voltage Range	4.5V to 40V	2.7V to 16V	4.5V to 24V
Output Voltage Range	1.2V to 37V	0.9V to 5.5V	0.8V to 24V
Max Output Current	3A	12A	3A
Switching Frequency	150kHz	600kHz-1MHz	500kHz
Price	\$5.20	\$2.24	\$1.04

After evaluating these options, the TPS54JA20 has been selected as our primary voltage regulator for the P.A.W.S. system due to the features it offers which lines up with our needs. This regulator offers up to 12A output current which compared to the alternatives, the LM2596 and MP2315, which are limited to 3A outputs, the TPS54JA20 provides significantly higher current capacity, aligning better with the project's demanding power requirements such as the Pi which can go up to 5A at full capacity. Additionally, it offers an adjustable output voltage range of 0.9V to 5.5V, and an input range from 2.7V to 16V, making it well-suited for both the high-power stepper motors and low-power components. With a switching frequency adjustable between 600kHz and 1MHz, it ensures efficient power conversion while maintaining minimal heat generation. Despite its enhanced performance, it remains affordably priced and includes support resources from Texas Instruments, including detailed design guides and PCB layout recommendations. These factors simplify integration and ensure reliability, making the TPS54JA20 the best selection for our regulators.

Chapter 4 - Standards and Design Constraints

This chapter discusses the industry standards and constraints relevant to the project.

4.1 Industrial Standards

Given the complex embedded nature of the project, it is important to consider several relevant industry standards. These standards emerged in response to the rapid technological and manufacturing advancements sparked by the Industrial Revolution. From the late 19th century to present day, their development has been instrumental in ensuring uniformity, interoperability, and safety across the diverse technology industry. The impact of these standards extends far beyond the United States, influencing on a global scale. The rise of international trade further emphasized the need for major industries to establish comprehensive standards that transcend national borders, facilitating collaboration and enhancing product quality.

4.1.1 IEEE Standards

Of the types of industrial standards, the ones pertaining most heavily to the project revolve around electronics. This is due to the presence of the two major embedded systems commandeering most of the hardware and optics via complex software. Therefore, the first standards to be discussed and analyzed are IEEE standards.

4.1.1.1 IEEE 2700-2017 - Standard for Sensor Performance Parameter Definitions

This standard provides a framework for the performance level we should expect from the sensors of the project. It's imperative that in the litter-box protection system, the optics subsystems --comprised of the IR proximity sensor and the doorway break beam-- behave consistently and with well-defined limits and operability to ensure the success and safety of the project. This pertains to tasks like detecting the presence of an animal at the front face of the enclosure or preventing accidental door closure on the feline.

This standard not only applies to the optics subsystem, but the pressure pad and PIR motion detector as well. These sensors' performance must also be measured to be consistent, as the pressure pad is a safety measure as well as a means of exit for the feline from the enclosure. Moreover, the PIR motion detector needs to function under well-defined conditions and limits as well to guarantee efficiency,

as over-detecting or under-detecting the feline inside the enclosure can cause inadvertent system issues.

4.1.1.2 IEEE 1872-2015 - Standard for Ontologies for Robotics and Automation

While no system in the project could be called a robot, this standard is relevant to the AI subsystem that does the animal identification. It provides a unified way of representing knowledge in autonomous systems, which is useful for structuring the animal identification algorithms, for defining the ontology for different types of animals (cats, dogs, other critters, etc.), as well as for ensuring consistency in how the system interprets and acts on sensor data.

4.1.1.3 IEEE 7001-2021 - Transparency of Autonomous Systems

The standard provides a framework for the transparency of autonomous systems. It establishes what amount of measurable and testable levels of transparency is needed to ensure that the AI systems under question can be objectively assessed. It states that when it comes to the operation and decision-making process of an autonomous system, it should be an understandable process so that users are able to trace back why and how the system made a particular decision. In regards to the project's AI-based animal-identification subsystem, because it relies on an autonomous mechanism to identify the felines using a camera and decide whether or not to allow entry, the standard's principles encourage the development of a method to trace back the data and logic that led the AI to that decision. This also makes it easier to identify the root cause of any errors in object identification in the AI model and prevent potential harm. Any malfunction of the plexiglass door or an incorrect animal detection will be traceable and fixable, reducing risks for the cat trying to use its litter box. Moreover, when users know that the system's actions are transparent and justifiable, they are more likely to have confidence in the full functionality of the system.

4.1.1.4 IEEE 802.15.1 - Bluetooth

This standard is directly applicable to the project, where Bluetooth will be used to enable communication between the Raspberry Pi (which controls the LCD screen that will display data for and to the user) and the mobile app on the user's smartphone. Adhering to this standard ensures the project will be compatible with a wide range of mobile devices, that there is a reliable connection and communication between the litter-box system and users' smartphones, and that the proper implementation of Bluetooth security features is established.

The latest version of Bluetooth is Bluetooth 5.3, but compatibility of this version with the Raspberry Pi model being considered for the project may be unlikely. However, later models of the Pi easily support Bluetooth 4.0 and later. Additionally, Bluetooth Low Energy (BLE) is particularly relevant for the project as it allows for low power consumption while maintaining a constant connection. This is ideal for sending data to the LCD screen as well as allowing the mobile app to receive real-time notifications about litter box usage or system status without extra power expenditure.

Additionally, when it comes to security, using Bluetooth facilitates this by using a process called pairing to establish a trusted connection between devices. This would allow exclusive control and access of pet data to specific authorized individuals. Additionally, the data being transmitted between the Raspberry Pi and the mobile app is encrypted, further ensuring a secure pairing process of the mobile app and physical enclosure. Not only that, but Bluetooth also uses adaptive frequency hopping to avoid interference with other wireless signals. This is important in a home environment where multiple devices (Wi-Fi, microwaves, etc.) are usually in frequent to constant operation.

4.1.2 ANSI/IES LM-80-21- LED Standard

The standard LM-80-21 is a very well-known and largely accepted way to look at the longevity and performance of not only visible LEDs, but infrared LEDs as well. Its premise is rather simple. It says that, if you want to know how long a light-emitting diode is going to last or how bright it might be in 10 years, you should expose it to high temperatures, measure its "lumen maintenance," and do this in a very specific way. After this, you can report the results and see if they are like or different from some other LED's results. This will give you a pretty good idea of how well an LED will age and how much light it will emit as it does so.

Our project, which requires the use of IR LEDs in a break beam and proximity sensor, stands to benefit greatly from the potentially useful metrics that LM-80-21 may provide. We have presented a scenario for which the IR LEDs are likely to be on either continuously or very nearly so during the intermittent obstructions the beam is designed to detect. Thus, it may be more relevant for us to consider how well the LEDs might perform under continuous operation, as they are close to doing that by design.

Furthermore, because our project is a capstone senior design project with possible implementations in real pets' lives, LM-80-21 compliance may be just what is needed to show that we comprehend the basic and vital requirements for durability and reliability that an IR sensor system must meet to be useful and effective in a mixed pet-household with "real world" applications. Not only may

this standard enhance the perceived quality of our design, but it may also provide some measure of quantifiable data that we can present to illustrate the robustness of our IR sensor system[21].

4.1.3 ISO 10110 - Lens Standard

An essential optics standard and guideline for the way in which optical elements (including lenses) are to be specified and described in technical drawings is ISO 10110. For our project, which employs IR LEDs and sensors to form a proximity and break beam detection system, this standard ensures that the elements used to direct or focus the IR light are not only up to snuff but also meet the kind of precise engineering demanded by the optics world if reliable performance is to be expected.

Incorporating ISO 10110 into our project can help set the expectations for lens manufacturers. This standard specifies tolerances that pertain to the appearance of a clear, distortion-free optical element: the quality of the materials used, the uniformity of those materials, and even the low level of detail that could be detrimental to the overall quality (in this case, as far as the use of IR light is concerned). Upholding such a standard in our project can be very beneficial to ensure that the lenses we select only contribute to a better accuracy and reliability of our sensor systems[22].

4.1.4 PCB Standard

PCB design standards are critical guidelines to ensure that our PCB is manufacturable, functional, and reliable. These standards, influenced by manufacturers' requirements and industry guidelines such as IPC-2221, establish criteria for aspects like trace widths, spacing, material selection, and component placement. Adhering to these standards not only simplifies the fabrication process but also enhances the overall performance and reliability of the PCB for its intended application in the system.

To ensure manufacturability, PCB producers establish precise criteria aligned with their fabrication capabilities. In our case, JLCPCB has been chosen as our manufacturer, and their guidelines include copper thickness options of 1 or 2 oz per square foot for double-layer boards, drill hole diameters ranging from 0.3mm to 6.3mm, and via dimensions requiring a minimum 0.3mm hole size with 0.5mm pads. Minimum trace widths are set at 0.127mm, with a required clearance of 0.3mm from the board's edge to preserve its structural robustness. Following these suggestions will keep compatibility with the manufacturer's processes and help reduce errors.

In addition to manufacturability requirements, IPC-2221 provides broader design guidelines to follow. Trace widths and spacings are outlined to maintain signal integrity and power distribution. Material selection is also important, with recommendations based on dielectric properties, thermal conductivity, and mechanical strength to ensure the board performs well under environmental and operational conditions.

Thermal management and trace routing are critical considerations for reliable PCB performance. IPC-2221 provides recommendations for effective heat dissipation, one of them being strategic placement of heat-generating components. Effective trace routing, particularly for high-speed signals, necessitates careful impedance management and strategies to reduce crosstalk, which are vital for preventing issues such as signal distortion or loss.

Lastly, IPC-2221 emphasizes the importance of component placement and design for manufacturability (DFM). Components should be positioned to minimize signal interference and optimize thermal flow while remaining accessible for assembly and testing. DFM principles ensure the design accommodates fabrication and assembly constraints, reducing costs and potential errors. Moreover, IPC-2221 outlines testing and evaluation procedures to confirm the mechanical durability and electrical performance of the completed board. These measures ensure the design adheres to industry benchmarks while maintaining reliability over an extended operational lifespan.

4.2 Practical Constraints

In the development of the P.A.W.S project, several constraints shape our planning, design, and implementation phases. These constraints can significantly impact our project's outcome, requiring careful consideration and strategic management to ensure the successful delivery of a functional system. There are many constraints to consider, but among the primary challenges are time, economic, and technical constraints. Time is critical since the project must be completed within the span of an academic year, necessitating efficient scheduling and prompt task completion. Economically, the team is limited by a tight budget, which restricts the selection of components, tools, and resources that can be utilized. Additionally, technical challenges related to the integration of various technologies such as facial recognition software, motorized doors, and safety sensors pose a potential risk to our project's success. Balancing these constraints while achieving the desired functionality requires planning, teamwork, and creative problem-solving to overcome any obstacles that may arise.

4.2.1 Time Constraints

Time management is one of the most significant challenges in our project, and it imposes constraints that heavily affect the building, testing, and overall progress of the system. In a project with tight deadlines, meeting each milestone on schedule is essential for success. Any delays in documentation, prototyping, or component integration could lead to severe setbacks. Missing even a single milestone could jeopardize the project's timely completion, potentially resulting in an incomplete final product.

Given that P.A.W.S. is being developed as part of our senior design course, our project must be completed within the constraints of an academic calendar year. This creates a rigid deadline that leaves no room for extensions. Our team must deliver a fully functional product within this period to meet the project requirements and course expectations. The pressure remains high to ensure that all phases—from design to implementation—are completed on schedule.

One of the critical time-related challenges is the need for thorough testing, debugging, and refining of the system to ensure that the motorized door mechanism, facial recognition technology, and safety sensors work seamlessly. Given the limited time frame, we must anticipate and address errors quickly. Unforeseen issues during construction or software integration could delay the schedule, especially if significant redesigns or troubleshooting are required. The time constraint, therefore, poses a threat to the overall success of P.A.W.S. due to the unpredictability of technical hurdles that may arise during the development process.

Another significant time constraint involves the procurement of parts, particularly custom components like printed circuit boards (PCBs) and specialized sensors. Delays in ordering and shipping, compounded by potential supply chain disruptions, can lead to project bottlenecks. If a critical part arrives late, it could delay testing and integration, which in turn compresses the time available for final testing and validation of the system. This issue is particularly pertinent given that certain components must be custom-ordered, and manufacturing delays can set back the project timeline considerably.

Moreover, fabricating specific elements of our system—such as the motorized plexiglass door and safety mechanisms—must be completed early to stay on schedule for the subsequent phases. The construction of these mechanical parts involves precise measurements, cutting, and assembly, which are time-intensive processes. If these tasks are not completed before the transition into the intensive testing phase, it may lead to rushed, suboptimal work that could compromise the quality and reliability of the final product.

The cumulative effect of these time constraints could force the team into making trade-offs between quality and timely delivery. Rushing through design, testing, or integration steps may result in a product that does not meet the initial performance goals or design specifications, leading to last-minute adjustments or the need to cut corners. Such compromises may jeopardize the integrity of the P.A.W.S. project and also increase the risk of failure.

To mitigate these time constraints, our team has committed to several strategies to enhance productivity and accountability. Core values like time management, consistent communication, and holding each other accountable to deliverables are vital. Our team ensures that every member is proactive in completing assigned tasks, minimizing the risk of delays. Consistent meetings, clear communication channels, and detailed project scheduling are crucial to staying on track.

In summary, the success of the P.A.W.S. project hinges on our team's ability to effectively manage their time, resources, and unforeseen challenges within the set deadlines. While the tight schedule presents significant constraints, the team's dedication to robust planning, clear communication, and early preparation provides a pathway to mitigate these issues and achieve a fully functional and reliable system within the academic year.

4.2.2 Economic Constraints

Another one of the primary challenges that our project faces is managing the economic constraints associated with its development. Being a student-led, self-funded project, P.A.W.S. must operate within a tight budget, which necessitates careful financial planning and judicious decision-making throughout the design and implementation phases. The limited budget places significant pressure on us to balance cost-effectiveness with system functionality, often requiring compromises on component quality, performance, and features to stay within financial limits.

The economic constraint is especially evident when selecting parts and materials. For instance, motorized mechanisms, sensors, and microcontrollers that power the door and facial recognition system must fit within the project's financial boundaries. However, choosing lower-cost components may lead to limitations in speed, accuracy, and durability, which can ultimately affect the performance of the system. We must prioritize affordability without sacrificing essential features, which involves a delicate trade-off between cost and performance.

To navigate these budget constraints, the team has to be strategic in sourcing parts and materials. An essential aspect of this strategy is keeping a reserve portion of the budget for unexpected expenses, such as component failures or

replacements during the testing phase. By setting aside a portion of the allocated funds, we can avoid potential delays if parts need to be re-ordered due to defects or damage during installation. However, this means further limiting the initial spending, which can create additional challenges in sourcing high-quality parts within a constrained budget.

Furthermore, the economic constraints impact decisions related to hardware and technology selection. For instance, while a more advanced microcontroller with built-in features could streamline the development process and enhance system capabilities, such options are often more expensive. Instead, we may have to opt for simpler, cost-effective alternatives that require more manual integration but fit the budget. This approach can save money upfront but may increase the workload and complexity of the software development phase, adding pressure to an already tight schedule.

Another aspect of the financial constraints is the need to optimize part selection for the automated door mechanism and safety sensors. High-quality motors and infrared sensors, essential for ensuring the safe operation of the cat door, can be costly. To keep expenses manageable, we may have to select less expensive components with lower power or durability ratings. This can result in increased maintenance and potential performance issues, especially if the components are subjected to rigorous, continuous use.

Supply chain issues can further complicate economic constraints. Ordering specialized parts like PCBs, proximity sensors, and motors may face delays due to supply shortages or shipping complications. It can be harder to source components quickly and at reasonable prices. These delays not only affect the budget due to increased shipping costs but also reduce the time available for assembly and testing, thereby compressing the timeline further.

Given these economic limitations, our team must employ strategic measures to make the most of the available budget. One approach is to conduct extensive research to identify cost-effective suppliers and take advantage of discounts or bulk purchasing options where possible. Additionally, we must leverage creative solutions, such as repurposing existing components or using open-source software tools, to reduce costs without compromising functionality.

Overall, the economic constraints impose a significant challenge throughout our project. They influence everything from component selection to system design, often forcing our team to make difficult decisions that balance budget limitations with project requirements. To overcome these challenges, thorough planning, strategic budgeting, and efficient resource management are essential. By maintaining a flexible yet focused approach, we aim to deliver a high-quality,

functional system within the confines of limited financial resources. However, these constraints also necessitate careful risk management to ensure that our project reaches completion on time and within a reasonable budget.

4.2.3 Technical Constraints

In developing our project, there are numerous technical constraints that we will navigate to ensure successful implementation. The goal of P.A.W.S. is to create a reliable automated access system that recognizes the user's pet cat and allows entry through a motorized door. However, building such a system introduces a range of technical challenges, from hardware compatibility to software integration, which must be addressed for the project to function as intended.

One significant technical constraint is related to the integration of the facial recognition technology needed for the access of the litter box. The project relies on a camera module capable of identifying the user's cat with high accuracy. However, we may be limited in some selection of hardware, which means opting for less advanced but affordable camera modules. These cameras may not have the processing power or resolution of higher-end models, potentially leading to issues with recognition accuracy, especially in low-light conditions or when the cat's appearance changes. To overcome this, the team must fine-tune the software algorithms to maximize accuracy despite the hardware limitations.

Another technical challenge involves ensuring the efficient operation of the motorized door mechanism. The door needs to respond promptly to the facial recognition verification while maintaining safety standards to prevent injury to the pet. However, integrating this motor system with the sensors and microcontroller presents its own set of constraints. The microcontroller must be able to handle real-time data processing from the sensors and the camera, while also controlling the motor to open and close the door. Ensuring this coordination requires careful selection of microcontrollers and efficient programming, but resource limitations mean we may not have access to high-performance processors. As a result, the system may face latency issues, especially when processing complex tasks, potentially impacting the responsiveness of the door.

Another possible constraint is the need for the P.A.W.S. system to operate independently of internet connectivity. Since the system is intended for home use, it must function offline to ensure privacy and reliability. This means that all facial recognition data processing must occur locally on the device, without the support of cloud-based services that could enhance accuracy or reduce computational load. The challenge here lies in optimizing the local storage and processing capabilities of the hardware to handle the recognition tasks efficiently. Limited memory and processing power in the microcontroller could lead to delays or

errors in identifying the cat, especially as the system's database of recognized images grows.

Furthermore, our project also faces constraints in terms of sensor integration. The P.A.W.S. system uses proximity sensors to detect when the cat is approaching, triggering the camera and recognition system to start. However, ensuring that these sensors function reliably in various lighting conditions and do not get triggered by other household pets or objects presents a technical challenge. Misidentifications could result in unnecessary door openings, which not only affects system efficiency but also poses a security risk. We must develop algorithms to filter out false positives and ensure that only the designated pet cat can trigger the access system.

Compatibility between different hardware components is another technical barrier that we need to address. Since P.A.W.S. involves integrating various subsystems—such as motors, sensors, cameras, and microcontrollers—ensuring that these components communicate effectively is essential. However, different manufacturers use different protocols and specifications, which may not always be directly compatible. We must, therefore, invest time in troubleshooting connectivity issues and ensuring that all parts are synchronized. This often requires custom firmware or additional adapters, which adds to the complexity of the system and can introduce new points of failure.

Additionally, power management is a crucial concern for our project. Since the system is designed to operate continuously, it needs to be energy-efficient to avoid excessive power consumption. We must optimize both hardware and software to minimize the system's energy draw, especially when it is idle. This may involve using low-power sensors or implementing sleep modes for the microcontroller, but these techniques can complicate the software design and potentially affect the system's responsiveness.

The final technical constraint involves the system's longevity and durability. As P.A.W.S. is intended for use in a household environment, it must withstand wear and tear, such as frequent door operation and exposure to dust or pet fur. Ensuring that the system remains reliable over time requires selecting components that can handle repeated mechanical stresses and environmental factors. However, the budget limits us to using mid-range parts, which may not have the same durability as more expensive options. This could result in increased maintenance requirements or the need for replacements, which could add unforeseen costs and delays.

In conclusion, the technical constraints we face span hardware limitations, software integration challenges, power management concerns, and system

longevity. Addressing these issues requires us to have careful planning, thorough testing, and strategic decision-making. We must continuously find creative solutions to optimize performance while staying within the constraints of budget and available resources. Ultimately, overcoming these technical hurdles will be key to delivering a reliable system that meets our project's objectives.

4.2.4 Safety Constraints

Also within our project are safety constraints, especially since our system directly interacts with the owner's pets. The design must prevent harm to their pets, ensure the structural integrity of the enclosure, and avoid causing injury during normal operation. For instance, the motorized plexiglass doors must include fail-safes, such as infrared sensors, to detect if the pet is in the doorway while the doors are closing. Without such precautions, the system could inadvertently trap or harm the pet. Similarly, any moving parts within the enclosure must be housed or shielded to avoid accidental contact that could lead to injury.

Furthermore, the electronics within the system must adhere to safety standards. Some electrical components may need to be insulated properly to avoid short circuits or malfunctions that could cause overheating or fire hazards. The power supply, which involves both high-current (for Raspberry Pi) and high-voltage (for stepper motors), must be protected to prevent damage or unsafe conditions. These measures collectively ensure that the P.A.W.S. system remains a secure and reliable tool for pet care.

4.2.5 Ethical Constraints

Ethical considerations for P.A.W.S. involve both animal welfare and user privacy. The system must operate in a manner that prioritizes the well-being of a pet, ensuring that it doesn't intimidate or harm the pet. For instance, any sounds or movements generated by the system should be designed to avoid distress. Additionally, the system must reliably recognize the designated pet, preventing unauthorized access by other pets, which could compromise the intended exclusivity of the enclosure.

Also from an ethical perspective, the components used in P.A.W.S. should be acquired from manufacturers that adhere to humane labor practices and sustainable production methods. This includes avoiding parts that may be produced through exploitative means. We do need to consider the ethical use of data, such as camera or sensor inputs. If the system includes any functionality that stores or processes information, ensuring transparency and obtaining consent from the user becomes essential to maintain ethical integrity.

4.2.6 Manufacturability Constraints

Manufacturability constraints in our project focus on producing a system that can be realistically built using available tools and resources, such as the Senior Design lab, and within a reasonable budget. Assembling the components requires careful design and ease of integration. Our system relies primarily on custom PCBs and motorized mechanisms, all of which need to be bought or manufactured. Balancing the cost of these components can be challenging, especially since durable materials are required to meet performance and safety standards.

Another significant factor is the availability and compatibility of parts. Custom components, such as the motorized door, must align with industry-standard specifications and ensure compatibility with the Raspberry Pi and other modules. Delays in fabricating components could hinder the assembly process too. Simplifying our installation and integration of the system can improve manufacturability.

4.2.7 Environmental Constraints

Our P.A.W.S. system must account for household environmental factors that could affect its functionality and lifespan. The enclosure and electronic components may be exposed to fluctuating temperatures, humidity, or dust depending on the location of installation in the house. The enclosure must withstand conditions that could possibly cause material deformation or electronic failure. Using components with appropriate temperature and moisture resistance ratings is essential to mitigate these risks.

Additionally, the system's environmental impact should be minimized. Materials used in the enclosure should ideally be recyclable or sourced sustainably. The energy consumption of the system, driven by the Raspberry Pi and motors, must also be optimized to ensure it operates efficiently without excessive power draw. This not only reduces the system's technological footprint but also contributes to operational cost savings for the user.

4.2.8 Sustainability Constraints

Sustainability for P.A.W.S. is important for the durability of the system and its environmental impact over time. The materials and components chosen must withstand prolonged usage without frequent replacements or repairs. For instance, the enclosure and doors must resist wear from repeated mechanical movement, while the electronic components must be shielded against corrosion or moisture infiltration. Durable design ensures a longer lifespan, reducing the need for part replacements.

Our project will also consider the broader sustainability of its production and operation. For example, energy-efficient components and low-power modes can reduce the system's environmental impact. Similarly, designing the system for easy upgrades or repairs, can extend its usefulness and reduce electronic waste. Sustainability in P.A.W.S. ensures it remains a responsible and impactful solution for pet welfare while minimizing external harm.

Chapter 5 - Comparison of AI-Generative Platforms

This chapter discusses large language models and how it's relevant to our project.

5.1 Large Language Models

Natural language processing (NLP) has its origins in natural language comprehension and text generation, and it is in these foundational areas that large language models (LLMs) have made their most significant impact. Yet, while LLMs are profoundly reshaping human-computer interaction, we don't understand them well; we don't understand what's going on inside them nearly as well as we do other kinds of computational models[23].

This innovation has inspired various models, most particularly GPT (Generative Pre-trained Transformer), which was developed by OpenAI. These models have changed the game for language generation; they now have the ability to perform unsupervised learning on an unprecedented scale using huge amounts of data. Eventually, these models became even more sophisticated and were released in advanced versions—like GPT-2, GPT-3, and GPT-4—that displayed astonishing capabilities in both comprehending and generating human-like written language. Although the model from OpenAI got the most public attention, another model had a huge impact—Google's BERT (Bidirectional Encoder Representations from Transformers). BERT was introduced in 2018[24] and changed the game for tasks like search and translation. In 2023, Anthropic introduced Claude[25], an AI assistant trained using constitutional AI principles, aiming to be helpful, harmless, and honest.

Since that time, LLMs have morphed into technologies that form the basis of further developments in AI, with the result that tasks have become increasingly automated and that an array of industries that depend on language processing have undergone significant transformations[26].

Advanced artificial intelligence systems trained on vast amounts of text data; large language models are some of today's most sophisticated intelligences. Using deep learning, typically with transformer architectures, LLMs understand and generate human-like text. They perform a range of natural language processing tasks—text generation, translation, summarization, and more—that are mostly defined by their ability to understand context and generate coherent, if not always entirely accurate, responses. They're used in everything from chatbots to content generation, virtual assistants to automated help desks. They're employed in those ways because of their talent for understanding and generating human-like

language. But also, because, like other types of AI, they're increasingly being looked to for ways to save money and labor, but at least sometimes, under the guise of providing better service to human customers[27].

5.1.2 Pros and Cons

There are multiple reasons one could give to recommend using LLMs for writing research papers. The first that comes to mind is that it is an excellent brainstorming tool. Everyone knows that writing something like a research paper generally requires a great deal of time. For some people, whose strong suit isn't writing, a tool like LLMs can serve to help "unblock" the writer's mind. Another important function that LLMs can serve in relation to research papers is the summarization of complex topics[28].

LLMs are useful for coming up with research questions and hypotheses because of its ability to engage in dialogue and supply different kinds of viewpoints. For a writing assistant, ChatGPT and other LLMs are good for structuring and clarifying the main arguments in a piece of writing, as well as for suggesting alternative ways of phrasing certain statements. ChatGPT could also aid in making a paper more understandable to a wider audience by providing explanations of complex concepts. At the same time, it could also help generate legitimate ideas for the kinds of case studies or examples that might make a paper's arguments more persuasive.

Nonetheless, it is very important to point out that though ChatGPT is a useful instrument, researchers should see it as a secondary source at best. All the information that researchers uncover, and use must be previously confirmed. Why? Because this seemingly simple program can and does suggest answers that are just plain wrong. And what's worse is that it can suggest wrong information in a way that is very hard to detect unless you're lucky enough to be exceptionally familiar with a topic beforehand. Also, are we being ethical if we use it and simply not tell on ourselves? Should we even be using it at all?

You might think you can trust the information, but that may not always be the case. First, you should know that the research paper you end up with may not be correct or accurate. Not up to the standard of a research paper that should be considered a genuine piece of work in the field. That's because ChatGPT and other LLMs themselves are not accurate, and it sure isn't accurate enough for you to use it as a source for a research paper[29].

The outputs of the model are limited to outputs that exist in the world. Not new or necessarily different from something that currently exists and/or is known. ChatGPT should not be viewed as some revolutionary new tool for conducting

research. This tool is not revolutionary because it doesn't really have the fundamental, necessary human-like intelligence and "understanding" of what constitutes high-caliber academic research—let alone the revolutionary capacities that mere human intelligence can provide if it's put into practice in the right way. At best, it is a more sophisticated Google Search. At worst, it can provide pathways to "academic" practices that aren't really that.

In addition, employing LLMs within a research context could have detrimental effects on the cultivation of certain vital skills, like that of critical thinking—essentially, the kind of skills you need to get by in life if you're not content to simply do what someone else has already done. When using content generated by artificial intelligence, one must consider not only the quality and utility of the content but also the ethics of its use. The most troubling ethical issue is plagiarism. Despite all of the safeguards, there are still some potentially seen as ethical violations when using AI to create content. Some even argue that using AI-generated content in a way that isn't disclosed could be considered a form of lying[30].

5.1.3 Using LLM's for Senior Design

For Senior Design, students can draw upon the massive computational power of ChatGPT and Claude to directly aid their creativity and productivity. It is a little like having a virtual team member, you can ask them questions you might ask of any smart person, with the added benefit that they are accomplishment-oriented and rarely require breaks. You can engage these tools in conversation. Each will give a slightly different answer to whatever you ask, and from their conversation, you should be able to get enough of a handle on the issue you are grappling with to make some design decisions, essentially with zero brain power on your part after you have posed the problem.

Despite their advantages, an over-reliance on the AI tools presents numerous drawbacks that can and do potentially infringe upon the learning experience of students. If students use AI to do the heavy lifting for solving problems or for generating text, they are likely to be thinking less rigorously and to be doing less solving of problems. Yet, we should not discourage students from utilizing AI. Increasingly, engineering students will find that AI is part of their working world. The question is how to use it in a way that is both educational and ethical.

Here are some ways AI language models, such as ChatGPT and Claude, might find application in the learning experience within the sphere of Senior Design:

- LLMs can aid in producing project ideas or expanding upon existing concepts. For instance, if you were to describe an initial idea for your project, the AI could

suggest related applications or potential expansions that might power your project to the next level.

- Debugging, using LLMs can offer quick help when faced with a technical issue. It could save you some much needed time as opposed to a simple google search.

- LLMs can help outlining, summarizing and proofreading.

These tools need to be used responsibly. They should enhance, not replace, the learning process. If the AI part of our project makes the experience too easy, then we have sacrificed the Senior Design reality for which we are supposed to be aiming. On the other hand, if we use AI in the project responsibly, then we can genuinely say that we have completed the project and gained just as much educational value as if we hadn't used AI at all[30].

Chapter 6 - Hardware Design

The following sections detail the critical components and systems of the AI-assisted litter box design. These include a Raspberry Pi schematic for processing and control, voltage regulator schematics for power management, optics schematics for the IR proximity sensor and break-beam sensor, and an MSP430 schematic. Additionally, the mechanical design elements are outlined, featuring the rail system for door movement and the stepper motor and driver schematic for precise motion control.

6.1 Proximity Sensor

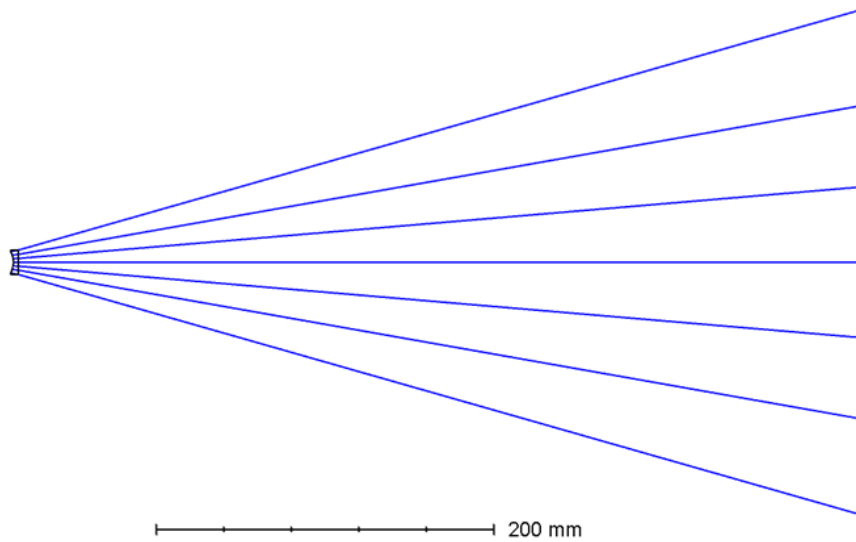
The proximity sensor for our AI-assisted litter box is designed to detect objects within a specific range, ensuring accurate and reliable operation. It utilizes an IR LED and photodiode system to sense objects by measuring reflected infrared light. The sensor is optimized for detecting small objects, like a cat, and is tuned to avoid false detections caused by environmental interference. By integrating this sensor with AI detection, we ensure that the door opens only when the intended user, the cat, is nearby, enhancing functionality and safety in mixed-pet households.

Table (6.1) - Proximity sensor engineering requirements.

System Metric	Requirement	Justification
Detection Range	1-1.5 ft	Range within which object detection is accurate
Field of View	45-60°	Ensures the system covers the necessary area
Response Time	< 3 seconds	Quick response to object presence

6.1.1 Lens Design

The lens design for the proximity sensor was carefully selected to achieve the intended field of view (FOV) necessary for detecting nearby objects effectively. A plano-concave lens was chosen for its ability to diverge light, enabling a wider FOV that ensures optimal coverage of the area near the litter box. This design allows the IR sensor to capture reflected signals from the desired detection range while minimizing blind spots. The plano-concave lens's specific curvature was tailored to balance range and resolution, providing accurate object detection within the required proximity.



	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT Standard ▾		Infinity	Infinity			0.000	0.000	0.000	0.0...	0.000
1	STOP Standard ▾	lens fron	-12.9...	3.000	N-BK7		6.350	0.000	7.211	0.0...	-
2	Standard ▾		Infinity	500.0...			7.211	0.000	7.211	0.0...	0.000
3	IMAGE Standard ▾		Infinity	-			149.305	0.000	149.305	0.0...	0.000

Figure (6.1) - Proximity sensor lens design on Zemax.

The desired field of view (FOV) for the proximity sensor was confirmed through simulations conducted in Zemax, a leading optical design software. Using a plano-concave lens, we approximated and optimized the divergence angles to ensure that the IR light covers the required area effectively. The simulation results

demonstrate the lens's ability to spread light across the target FOV, enabling accurate detection of nearby objects while minimizing interference outside the defined range.

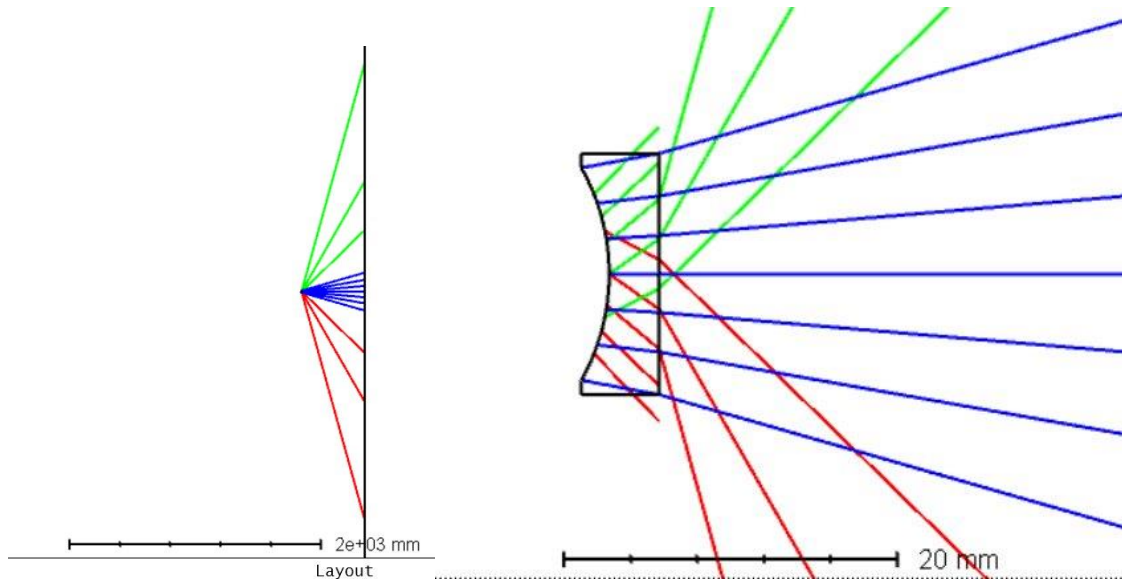


Figure (6.2) - Proximity sensor lens design on Zemax showing different optical fields.

The Zemax output includes ray-tracing diagrams that clearly illustrate how the lens diverges light at various angles. These diagrams highlight the successful achievement of the intended FOV by showing the range of angles at which the lens redirects light. By analyzing these angles and their distribution, we verified that the lens design meets the project's requirements for proximity sensing, ensuring optimal functionality and reliable object detection.

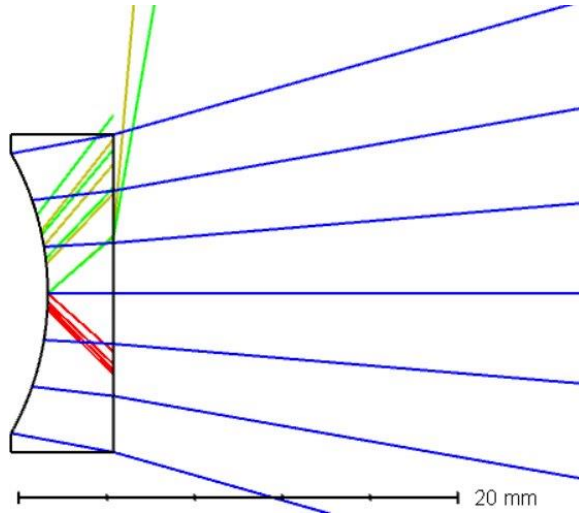


Figure (6.3) - Proximity sensor lens design on Zemax showing the refraction limits of the lens.

The final image above illustrates the refraction limits of the lens, showing the angles at which the reflected IR light can no longer be effectively captured by the sensor. This limit occurs at angles exceeding 85 degrees, where light rays are too dispersed to be detected reliably. However, this limitation does not impact our design, as the project only requires a field of view (FOV) of approximately 60 degrees. Within this range, the lens performs optimally, achieving consistent divergence and reflection capture. The additional margin beyond the project's FOV ensures robust operation while maintaining efficiency and accuracy in detecting objects within the intended proximity.

6.1.2 Circuit Design

The figure below provides an illustration of how the circuit and schematic of the proximity sensor will be integrated into the system; in Chapter 9, we will demonstrate a working prototype for this subsystem. It highlights the configuration of the IR LED and photodiode, showing their strategic arrangement to enable a wide field of view (FOV) for detecting nearby objects. The plano-concave lens is depicted as dispersing the emitted infrared light, ensuring broader coverage and improved detection sensitivity within the sensor's operational range.

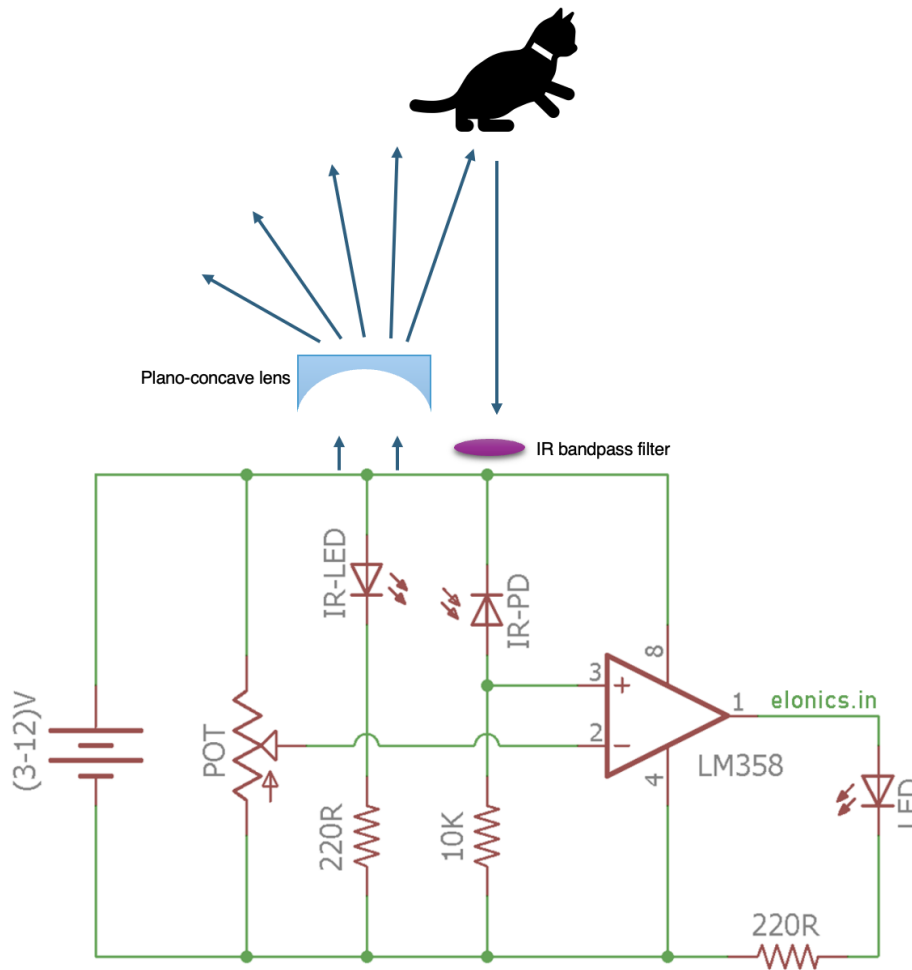


Figure (6.4) - Proximity sensor circuit[31] and schematic illustrating the object detection.

The image also depicts an infrared bandpass filter. An essential part of the proximity sensor, this filter boosts the system's performance. An IR bandpass filter allows light within its specific range—around 940nm in our case—to pass through and block everything else, including other wavelengths of infrared light and most importantly for our purposes, ambient light, which in many situations is a significant source of interference. This ensures that the photodiode primarily detects light emitted by the IR LED, improving the system's sensitivity and accuracy. In our setup, the bandpass filter is placed in front of the photodiode, reducing the noise from stray visible light and other IR sources in the environment.

6.2 Break-beam Sensor

The break beam sensor inside the litter box is a critical safety feature designed to ensure smooth and secure operation. Positioned just at the door, the sensor consists of an infrared emitter and a receiver placed opposite each other to create an invisible beam across the entrance. When the beam is interrupted, it signals the system that an object—such as the cat—has entered or is in the process of entering the litter box. This prevents the door from closing prematurely, ensuring the cat's safety and avoiding mechanical strain on the system. By integrating this real-time monitoring capability, the break beam sensor adds an extra layer of reliability to the overall design, ensuring seamless functionality for the AI-assisted litter box.

Table (6.2) - Break-beam sensor engineering requirements.

System Metric	Requirement	Justification
Detection Range	12 in	Range within which object detection is accurate
Field of View	<10°	Ensures the system covers the necessary area
Response Time	< 3 seconds	Quick response to object presence

For the break beam sensor, we opted not to include a lens in the design because the IR LED and photodiode we selected were inherently well-suited for our project's requirements. The chosen components are capable of creating a reliable and focused beam across the small span of the litter box door without the need for additional optical elements. The IR LED provides sufficient brightness and directionality, while the photodiode's sensitivity ensures consistent detection of the beam interruption, even under varying lighting conditions.

Since the beam's range only needed to span the width of the door, the inherent characteristics of the selected components eliminated the need for extending or focusing the beam further. This simplified the design and reduced potential alignment issues that might arise from adding a lens. By leveraging the natural compatibility of the IR LED and photodiode, we achieved a robust and efficient break beam sensor that meets the project's safety and functionality requirements without unnecessary complexity.

6.2.1 Circuit Design

The figure below provides an illustration of how the circuit and schematic of the break beam sensor will be integrated into the system; in chapter 9 we will show a working prototype for this subsystem. It highlights the configuration of the IR LED and photodiode, showing their precise alignment to create a focused beam that serves as the detection mechanism.

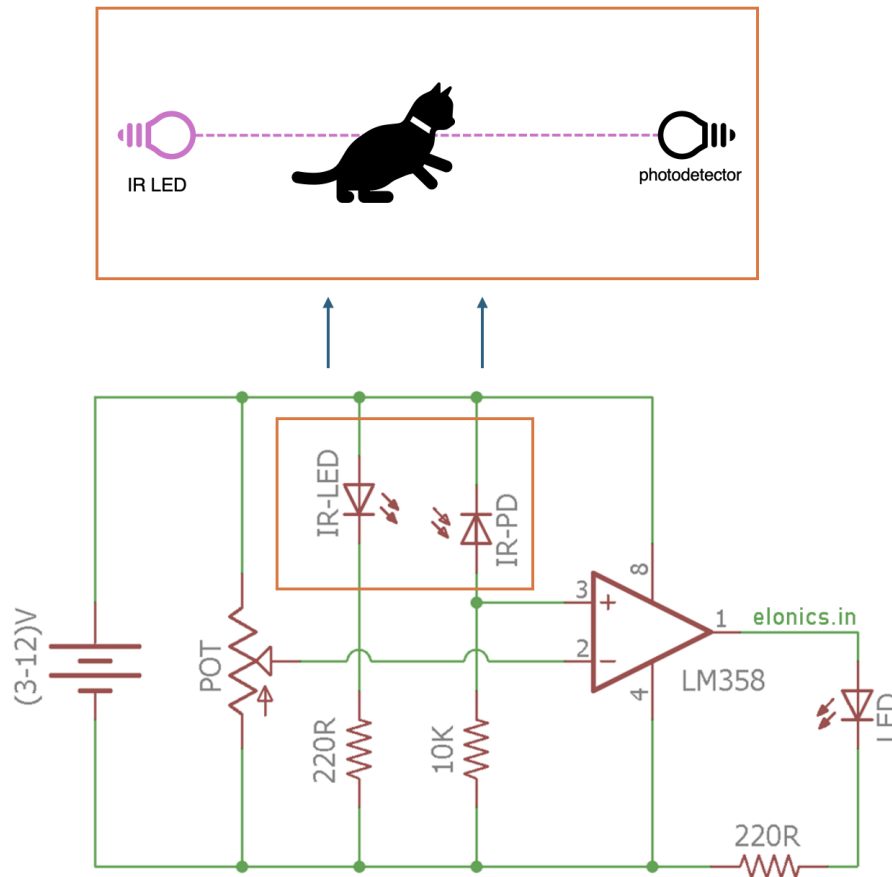


Figure (6.5) - Break-beam sensor circuit[31] and schematic illustrating the object detection.

6.3 Power Delivery System

The power system for P.A.W.S. is designed to ensure efficient and stable power for all of our components. Power is initially drawn from a standard AC outlet

through a 12V AC-DC power adapter, which serves as the primary input source. This 12V supply is then distributed and regulated to meet varying voltage requirements. Specifically, the stepper motors are powered directly from the 12V, while the Raspberry Pi and MCU PCB require voltage regulation down to 5V and 3.3V, respectively.

6.3.1 DC/DC Converters

To achieve both required step-down voltages, two separate voltage regulators will be implemented directly to these elements. One voltage buck converter will step the 12V down to 5V, delivering sufficient current and power to the Raspberry Pi, which has significant power demands, including peripherals. Additionally, a secondary voltage buck converter will step the 12V down to 3.3V to power the MCU PCB and other associated components. This separation ensures operation on a clean, stable voltage while minimizing noise and interference from high-power components such as the motors.

Our design initially used WEBENCH, a designer tool provided by Texas Instruments, to help outline the type of DC/DC conversion that will best suit our needs. We decided to utilize the TPS54JA20 voltage buck converter for both step-down voltages. This buck converter can step down an input range of 2.7V to 16V down to 0.9V to 5.5V which is exactly within our range that we require for both voltages. The max current output is up to 5A for the Raspberry Pi at maximum usage. The buck converter also has this covered because it can output a current up to 12A. Looking at the datasheet for the TPS54JA20, we will follow its recommendation to use ceramic capacitors. The desired output voltage is programmed by the voltage divider between resistors RFB_HS and RFB_LS, using this equation: (insert equation here), where RFB_LS is recommended to be 10 k Ω . To step the 12V down to 5V, RFB_HS = XX k Ω and to step the 12V down to 3.3V, RFB_HS = XX k Ω . Shown next are the schematics for the 5V and 3.3V voltage regulators respectively using LTSpice:

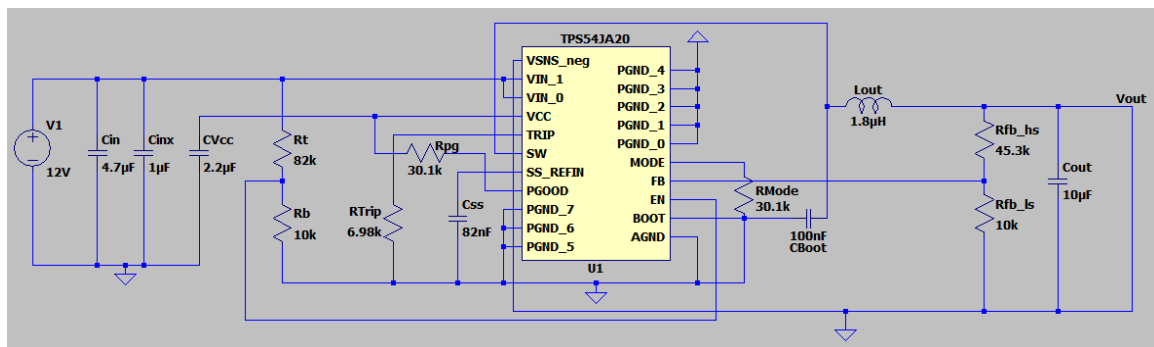


Figure (6.6) - 12V Step Down to 5V Voltage Buck Regulator Schematic

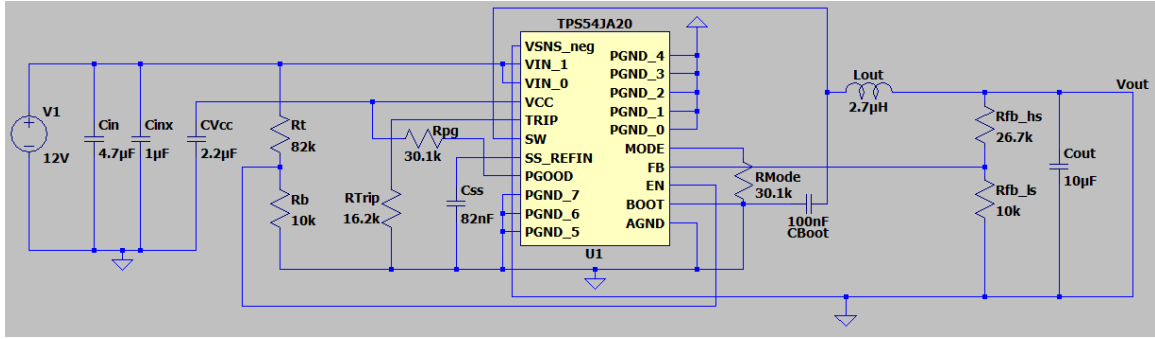


Figure (6.7) - 12V Step Down to 3.3V Voltage Buck Regulator Schematic

6.4 MSP430

The project will be using an MSP430G2553 as part of the Main PCB system. This MCU was selected for its numerous ADC pins, UART capabilities, simple architecture, and ultra-low power consumption. Refer to the appendix.

6.5 Overall Schematic

The hardware system for P.A.W.S. integrates multiple components using EasyEDA Design Software[32] to create a cohesive and efficient setup. Initially, the voltage regulators are supplying the necessary power levels to various components. A 3.3V regulator will provide stable power to the ESP32 MCU, which manages sensor inputs, motor control, and communication with other devices. The Raspberry Pi 5, responsible for processing the facial recognition system, will receive 5V power, as will the IR proximity sensor, IR break beam sensor, and pressure pad sensor. Additionally, the stepper motors, which drive the movement of the plexiglass doors, will be powered by a 12V supply.

The Raspberry Pi and ESP32 will communicate together, with the Raspberry Pi handling computationally intensive tasks like image recognition and the ESP32 managing real-time sensor data and motor control. Motor drivers connected to the stepper motors will utilize a rail system to smoothly open and close the plexiglass doors, ensuring safe and efficient access for the cat. The Figure 6.8 below shows our integrated design, which ensures all components work together to meet our performance goals.

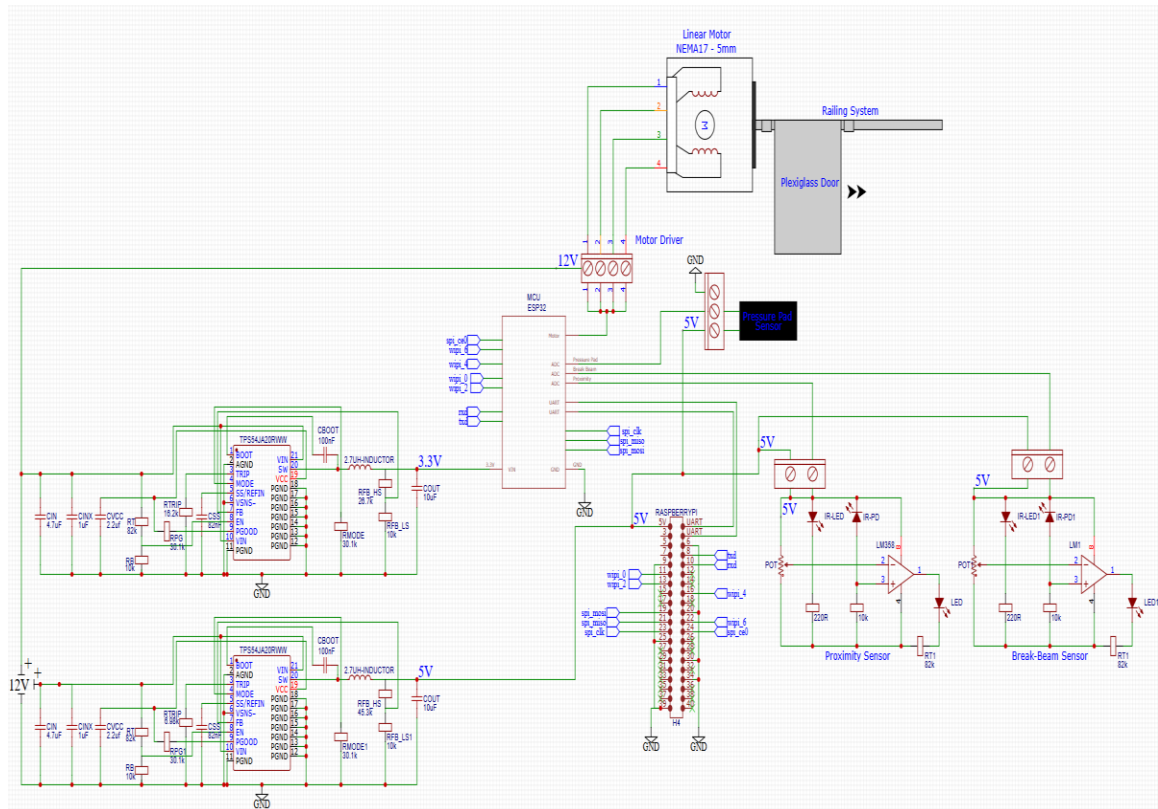


Figure (6.8) - Overall Schematic (using EasyEDA Circuit Design Software)

With the overall schematic integrating many subsystems, it may be tough to follow some of the connections we previously explained. Therefore we have provided the following Figure 6.8 a) and b) that better helps showcase the layout of the overall schematic and how we will implement each piece together.

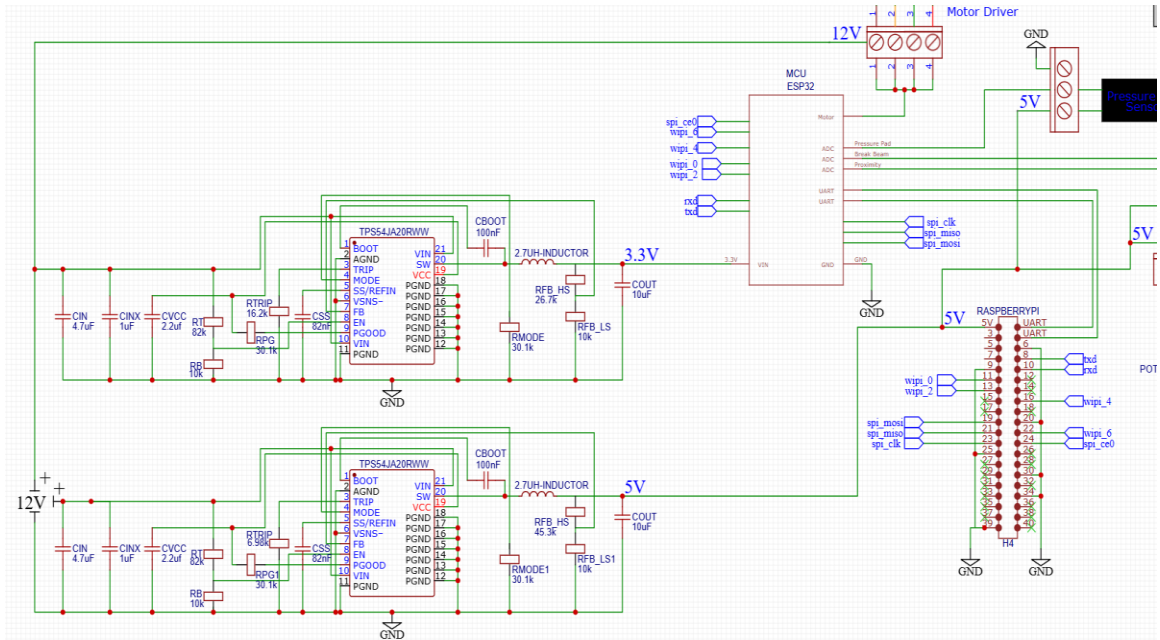


Figure (6.9 a) - Partial Overall Schematic Showing Voltage Regulation Integration (using EasyEDA Circuit Design Software)

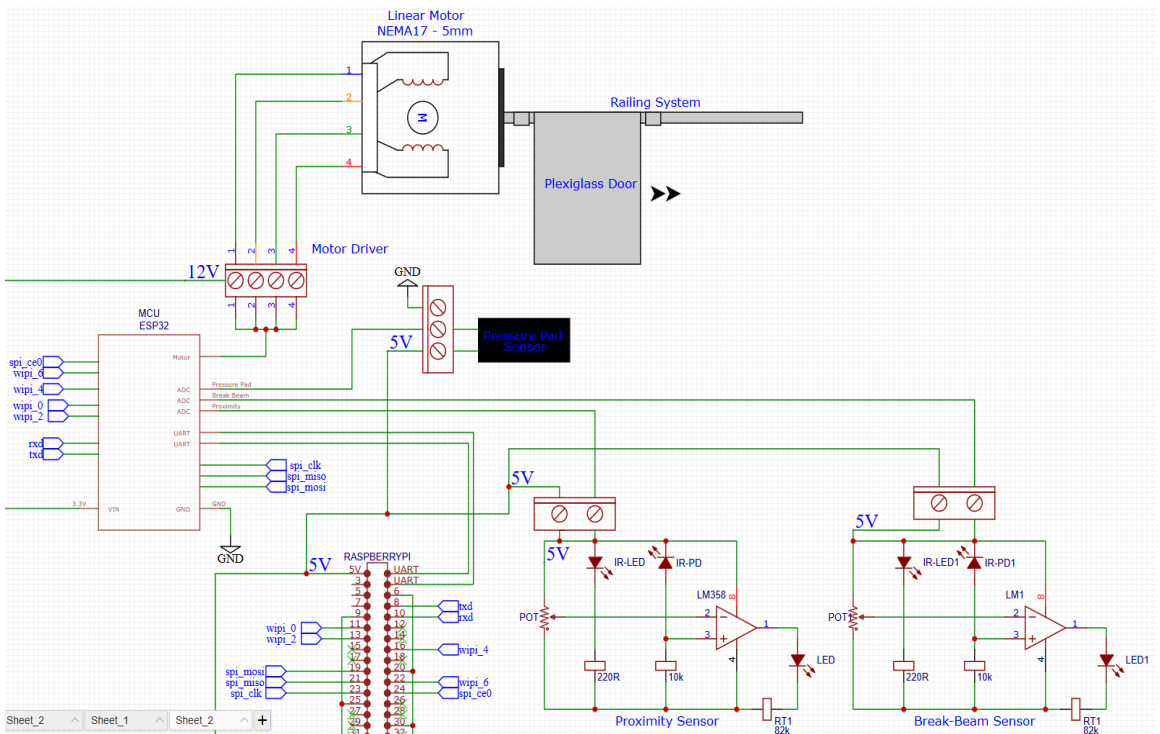


Figure (6.9 b) - Partial Overall Schematic Showing Sensors, Raspberry Pi, MCU, and Motors Integration (using EasyEDA Circuit Design Software)

Chapter 7 - Software Design

This chapter discusses the design plans for any software elements of the P.A.W.S. project. This includes an overall flowchart of the entire enclosure's operations, descriptions of specific technologies used in the designs of the machine learning and mobile application software, and early prototype testing of the machine learning algorithms.

7.1 Machine Learning Software Design

This subsection includes a flowchart of the entire machine learning software process and detailed descriptions of each notable step. It also discusses the specifics of the chosen model, dataset, and libraries used.

7.1.1 Machine Learning Process Flowchart

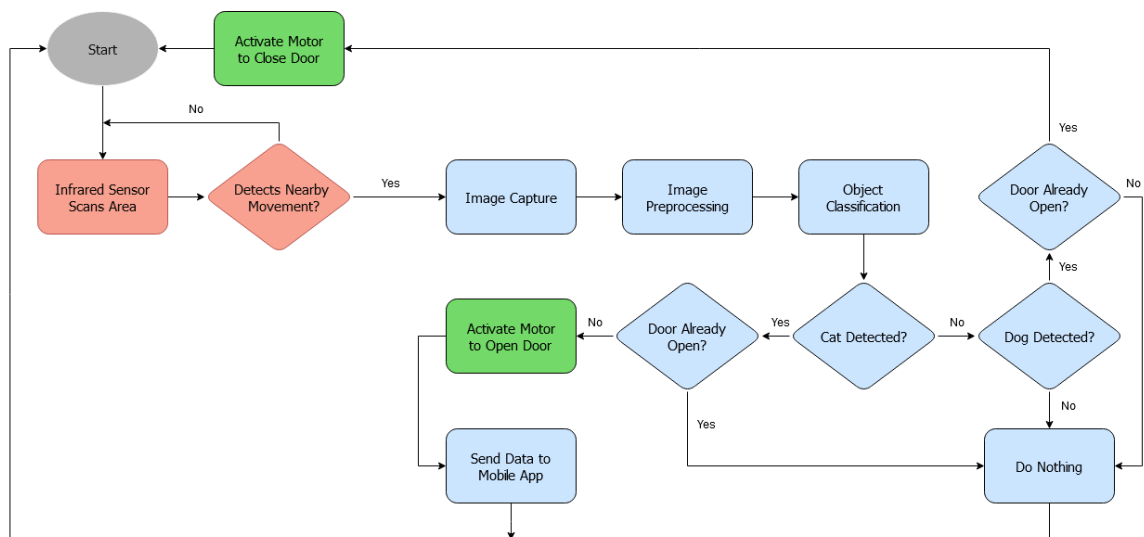


Figure (7.1) - Computer vision flowchart actions, decisions, and looping.

Above is a basic flowchart for the software process required to complete the machine learning object detection and recognition tasks. Areas marked in red are optical components, green are electric motorized door controls, and blue are any software sections related to the machine learning algorithm. Each blue section is explained in more detail below.

7.1.1.1 Image Capture

The image capturing stage of the machine learning software flowchart begins when the IR LED and photodiode proximity sensor system detects movement

within a foot of the entrance to the enclosure. If this occurs, the microcontroller will notify the Raspberry Pi 5 to begin operating. The connected Raspberry Pi Camera Module 3 will take a continuous video of the P.A.W.S. enclosure's surroundings and send each frame as an individual snapshot back to the Pi for processing.

7.1.1.2 Image Preprocessing

In the image preprocessing stage, the Raspberry Pi receives a constant stream of image data from the camera module. Each image is resized and normalized for overall consistency and to be easier for the model to later classify.

The Raspberry Pi Camera Module 3 can take images as large as 4608 x 2592 pixels, but doing so would significantly slow down the entire ML workflow. Without lowering the resolution, the Pi will not be able to reach even 1 FPS (frames per second), which would make consistent detection and classification over time much more difficult. By lowering the resolution to a more modest 640 x 640 pixels or even 320 x 320 pixels, we can see frame increases of 20 FPS or more. This does, however, come with the tradeoff of lower processing performance. The smaller the image, the harder the trained model must work to reliably detect anything meaningful. At low enough resolutions, the model will not be able to detect any objects at all. The tradeoffs between image resolution and processing performance will need to be evaluated during the prototyping stages of the project.

7.1.1.3 Object Detection and Classification

The object classification stage is where the bulk of the processing power is required. This is when a trained model will detect objects inside a given image and attempt to recognize them as part of a predefined set of classes. For P.A.W.S., required classes only include cats or dogs, and so the model will only search for and classify either of these animals. In this step, we only consider a positive classification if the model has an identification accuracy of at least 90%. Because some dogs and cats might look similar to a simple or undertrained ML algorithm, it is vital that the system is extremely confident in its identification.

7.1.1.4 Decision Making

Once the model has made a confident recognition that a cat or dog is present in a given image, the system has to then decide if it should trigger the motorized door or not. Ideally, the same animal should be consistently detected for around 3 - 5 seconds before the system makes a final decision. This is because we don't want the door to open if a cat is simply passing in front of the enclosure with no

intention of actually entering. If a cat is detected as clearly trying to enter the enclosure, then the Raspberry Pi can signal to the microcontroller to open the door. Otherwise, if a dog is detected then the microcontroller will simply do nothing. Either way, the owner will receive a notification on their mobile device that an animal was trying to enter the enclosure, and a snapshot will be saved in the mobile app.

Whether or not to signal the microcontroller for door controls is perhaps the most important decision to make. A simple decision to make is if the door even needs to be controlled at that moment. From the flowchart, we can see that if a cat is detected as trying to enter when the door is already open, there is no need to signal for any control. Similarly, if a dog is trying to enter but the door is already closed, there is again no need to signal for any door controls. The only two states where the door might need to be activated is when the door is closed and a cat is trying to enter, or when the door is open and a dog is trying to enter. However, it is vital that the door does not close when a cat is inside the litter enclosure, and especially when it's inside the doorway, regardless if a dog is detected or not. This is the primary safety concern that must be under heavy consideration at all times.

7.1.2 Machine Learning Models and Libraries

The following subsection details the specific model and libraries used for completing the project's computer vision inference tasks. It also lists the image dataset used in the initial training of the model for prototyping purposes.

7.1.2.1 YOLO Vision Model

YOLO (You Only Look Once) is a family of vision models built for real-time object detection and recognition. These models are among the fastest available as a result of their single pass recognition ability. Basically, while other models may need to look over an image multiple times before successfully identifying objects, YOLO is able to do so in just a single pass through.

An important deciding factor for using the YOLO models specifically is its use of grid-based prediction. This means that the model can find certain objects and mark exactly where they are in the image. This has the benefit of being able to detect multiple objects at once, even if they overlap slightly. For example, in an image that has both a dog AND a cat, some models will only be able to detect one or the other. YOLO, however, is able to detect both animals with a high level of accuracy and track their motion within a set of images.

The most recent iteration of YOLO is YOLO11, however the P.A.W.S. project will instead be using the previous version YOLOv10. This is because YOLO11 is only about a month old at the time of writing and isn't a completely stable release yet. Luckily, YOLOv10 is able to execute tasks at nearly the same performance as the v11 version and will still be powerful enough for our classification tasks.

7.1.2.2 COCO Dataset

The YOLO model is initially installed pre-trained off a large dataset called COCO (Common Objects in Context). This dataset was created specifically for object detection systems. Notable features are that it includes over 330 thousand images with over 200 thousand of which being pre-labeled, 1.5 million individual object instances, 80 different object categories, and at least 5 captions for every single image which helps the model more accurately identify objects.

For P.A.W.S. specifically, the COCO dataset notably already has predefined and trained classes for both cats and dogs. However, scrolling through the dataset's images shows that almost all of them are under normal lighting conditions. The Raspberry Pi camera module used for this project is the NOIR version, which lacks an infrared filter on the lens unlike the regular IR version. This means that our images will be more washed-out in saturation but gives the project the ability to see somewhat clearly during pitch-black nighttime scenarios. The YOLO model will almost certainly still be able to detect and recognize a cat despite the washed-out colors. However, we cannot guarantee the same success during nighttime testing when images lack any color, have inconsistent lighting, and will be fairly dim.

As a result, we have decided to continue using the pretrained COCO dataset only during initial prototyping and testing. For the fully completed project, the YOLO model will be retrained with a new custom dataset of images that will help guarantee accurate recognition during any time of the day. This new dataset will include images of cats and dogs during both daytime and nighttime lighting, as well as with both fully saturated and completely unsaturated colors. Although detection will be less accurate in certain scenarios because of the significant reduction in dataset size, this decision allows a higher degree of flexibility and finer control of details when tuning the model.

7.1.2.3 OpenCV Library

OpenCV (Open-Source Computer Vision) is an open-source library that provides algorithms to more easily and efficiently run computer vision models. Although the library was built using C and C++, OpenCV is natively compatible with all versions of the YOLO model family from version 4 and up. The only exception is

that it is not yet compatible with YOLO11, which is why it was explained earlier that P.A.W.S. will utilize YOLOv10 instead.

Some important functions provided with OpenCV include creating text and bounding boxes around objects, converting images to different color schemes (BGR to RGB for example), and displaying final annotated result frames.

7.2 Mobile Application Software Design

The following sections detail each major component in the software design of the integrated mobile application. Each subsection describes a specific page in the app, such as its design and overall function.

7.2.1 Sign Up / Log In

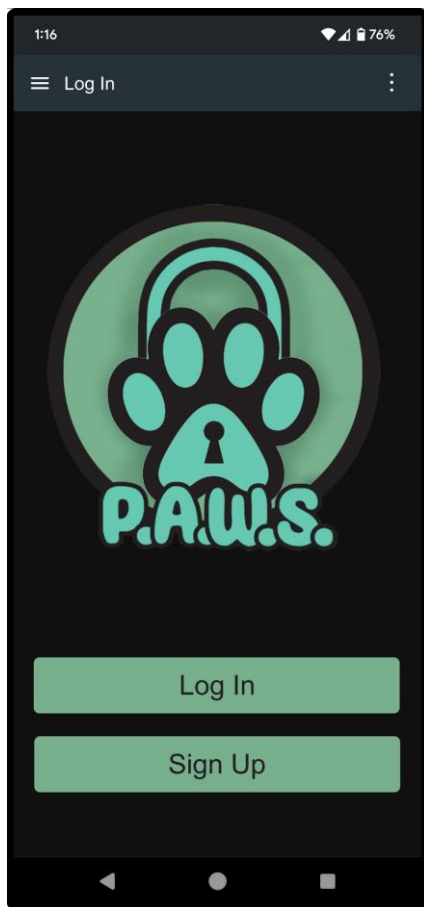


Figure (7.2) - Design for the initial landing page.

Upon opening the mobile app after the first installation, or when opening it while not currently signed in, the user will be greeted with the initial landing page. This simple page has two buttons for either logging into an existing account or creating

a new one. Each of these buttons will take the user to its own respective page below.

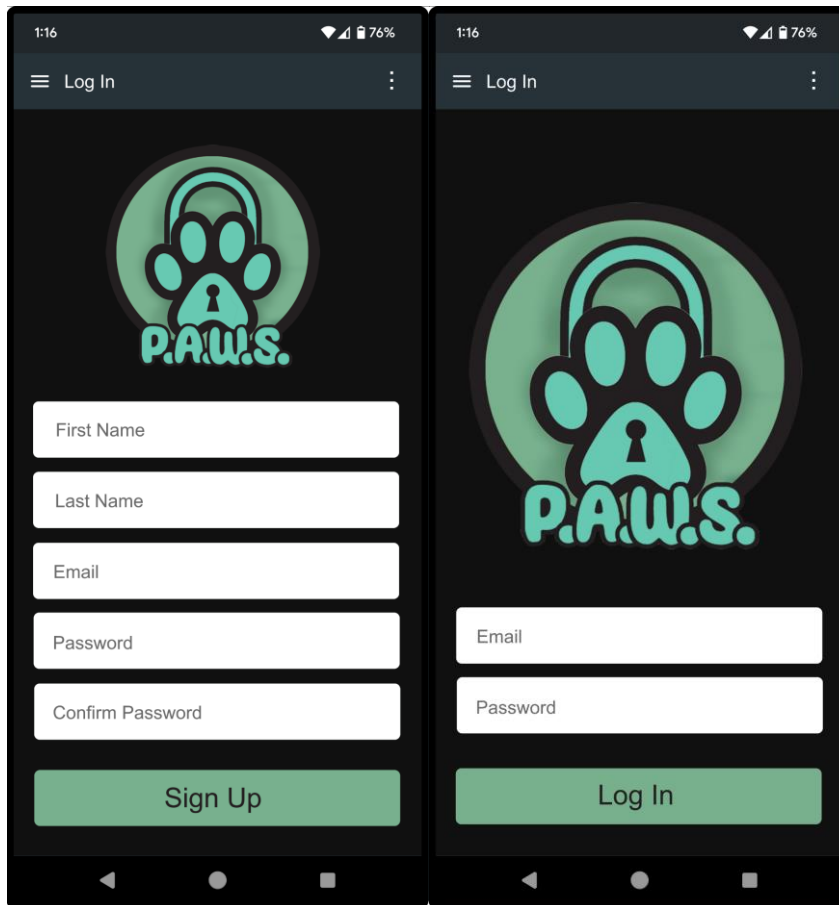


Figure (7.3) - Designs for the sign up page and log in page.

If a user does not already have a pre-existing account, they can choose to sign up for one. In order to prevent fake bot accounts, the user will be prompted to enter their name and email address. When the signup is complete, a verification email will be sent to the entered email address. If properly verified, the user will have full access to the app and can then connect to their owned P.A.W.S. enclosure through Wi-Fi. Also, the user must enter a password for their account, and then successfully confirm this password by writing it exactly the same way in the field after. All of this data will be sent and stored into the project's accounts database. Although not included in the design mockup, there will also be a "forgot password?" button that will take the user to yet another page. That page will allow the user to enter an email address, and if found will send a new verification email. This email will allow the user to reset and change their password, with the new password overwriting the old one in the database.

In the case that the user does already have a P.A.W.S. account, they can click on the “Log In” button from the main landing page. This leads to a very simple page with two enterable text fields. The user will be prompted to enter their valid email and connected password. When pressing “Log In”, the entered details will be temporarily stored and an attempt will be made to search for them inside the main accounts database. If the found email and password are both valid, the user will be taken to the main “Home” page. If invalid, the app will let the user know that either the email or the password was incorrect and reset the text fields.

7.2.2 Home

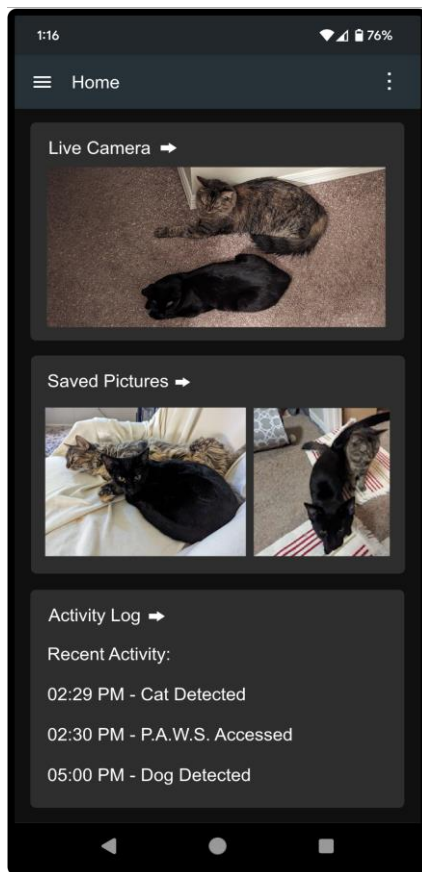


Figure (7.4) - Design for the main Home page featuring tabs that allow the user to enter any other functional pages of the app.

Once the user has successfully logged in to their account, the P.A.W.S. Home page is where they will be able to access everything that the app has to offer. There are three main tabs that lead to the primary features of the project's app: the live camera, saved pictures, and activity log. The top bar also features a side menu, openable from the icon with three lines. This side menu can be accessed from any of the pages, and features tabs that allow the user another way to easily

navigate through the app. On the far right of the top bar is a small three vertical dotted icon that, when pressed, can bring up the settings menu. The settings menu can also be accessed at the bottom of the side bar. While the live camera will simply be a static image, the “Saved Pictures” and “Activity Log” areas will change depending on the most recently saved images and detected activity around the enclosure.

7.2.3 Saved Pictures

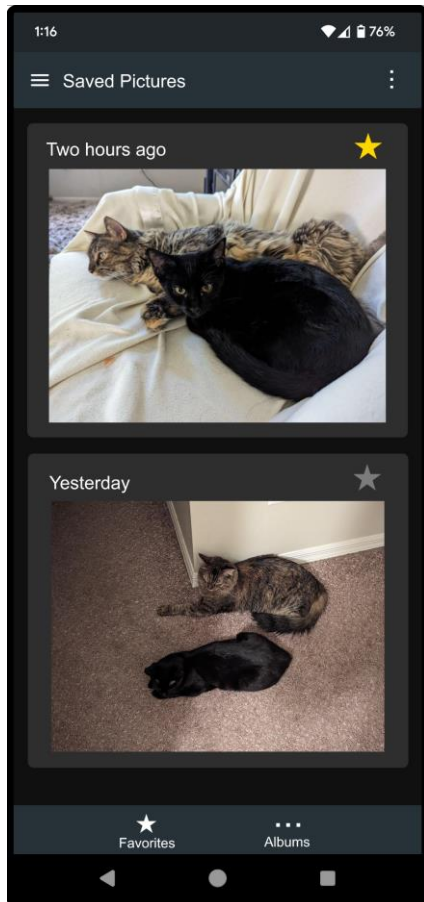


Figure (7.5) - Design for the Saved Pictures page where the user can view, favorite, and sort any images that the enclosure saves.

The “Saved Pictures” page is where P.A.W.S. stores any important image snapshots it takes. Important images will be taken whenever the motorized door is triggered to open, so they will always be snapshots of the cat that is actively entering the enclosure. When a new user successfully creates an account, they will also have a new images database assigned to them. This database is where all saved images will be stored, and can only be accessed by that singular valid user.

From this page, the user has a few different options for handling pictures. Though not pictured in the above design, there will be a small settings menu, similar to the one in the far right of the top bar, that will allow the user to delete a snapshot from the database. There will also be an option for sorting the snapshot into a chosen photo album. Next to the dropdown menu will be a star that, when selected, will sort the photo into a special “Favorites” tab. The favorites and albums tabs are in a bottom bar and will take the user to each of their respective function pages.

7.2.4 Activity Log

The activity log page is where the user can view any important events that have recently occurred in or around the P.A.W.S. enclosure. This will include details such as if an animal was detected, what kind of animal it was (cat or dog), if the enclosure was accessed, and if the door was closed due to detecting a dog. Each event will be time stamped and saved to the activity log database, which, similarly to the saved pictures database, is automatically created and connected to any new accounts. The activity log will be a fairly basic text-only page with an infinite vertical scroll. As of SD1, it is undecided if this page will require an automatic sorting system for each unique event. If this does end up being implemented, then there will be a bottom bar on this page where the user can filter by event type.

7.2.5 Live Camera

The live camera page is currently the only stretch goal of the mobile application, and further research and implementation decisions will be completed only after the other major components are functional. If added, this page will feature a single video player that links through WiFi to the Raspberry Pi Camera Module 3. When there is no object currently being detected by the optical system, the camera module would normally be in an idle state. If the user decides to view the live camera feed, this will trigger a wake-up on the camera, similarly to if an object was detected. The camera module will stream a live video feed straight to the app rather than to the YOLOv10 model, so the user should never see the backend workings.

7.2.6 Settings

Finally, the settings page is accessed from either the top bar or at the bottom of the side menu. This page allows the user to change any details regarding either the enclosure or the app itself. Currently planned settings features include managing the LCD screen, setting specific times of day that the enclosure can be accessed, and changing the color theme of the app. Here, a user can also change

their connected password similarly to how they can change the password through the “forgot password?” button on the log in page. The settings page, similarly to the activity log, will comprise mostly of plain text with some icons for easy accessibility.

Chapter 8 - System Fabrication/Prototype Construction

8.1 PCB

A critical aspect of our project is the development of a custom PCB to house and integrate the majority of P.A.W.S. system's components. We have established a set of technical guidelines to follow throughout the design process, ensuring the PCB will meet functional and operational needs. Through comprehensive research into PCB manufacturing, we have considered design principles that will guide our development process.

8.1.1 PCB Design Software

First topic when designing the PCB for P.A.W.S., we had to decide which PCB design software to use. We will assess three popular PCB design software tools to choose from: CADsoft Eagle, KiCAD, and EasyEDA. Each of these tools offers a range of features suitable for designing and fabricating PCBs, making them widely used in electronics design. We will evaluate each software to determine which one best fits the requirements, and is the most efficient tool, for our project.

8.1.1.1 CADsoft Eagle

CADsoft Eagle[33] offers a well-established PCB design software that has been in use for many years. Because of its longevity, there are a lot of resources available online, making it easier for us to find help when needed. One of Eagle's strengths lies in its extensive component libraries, along with its flexibility to import an unlimited number of external components into a project. This capability is particularly useful for us to access parts that aren't readily available in other design software. However, Eagle can be challenging to learn, due to its extensive set of tools and complex user interface.

8.1.1.2 KiCAD

KiCAD[34] is an open-source PCB design tool known for its flexibility and feature-rich environment. As completely free software, KiCAD provides a powerful set of tools which covers schematic capture and PCB layout to circuit simulation, making it suitable for designing complex boards. One of KiCAD's key advantages is that it is open source, which ensures regular contributions to a growing library of components. KiCAD is highly customizable, which may allow us to develop custom libraries and scripts to tailor to our project. One downside is managing component libraries can be not as efficient as other PCB design tools.

8.1.1.3 EasyEDA

EasyEDA is a cloud-based PCB design software that can be accessed anywhere with an internet connection, providing flexibility and convenience. EasyEDA is also a free to use option, making it an ideal choice for our project. In addition, EasyEDA includes numerous tutorials and open-source projects, which are particularly helpful for circuit and PCB layout design. Furthermore, EasyEDA is integrated with LCSC, an electronic component supplier, allowing us to easily find and source components for the design. It also includes built-in SPICE simulation tools, allowing us to test and validate any of our circuits before moving to the fabrication stage. However, as a cloud-based tool, EasyEDA requires a stable internet connection, which may pose a challenge with unreliable connectivity.

8.1.1.4 Conclusion

After careful consideration of these three PCB design software tools, we have decided to use EasyEDA for the P.A.W.S. PCB. Its ease of use, intuitive interface, and integration with online libraries and simulation tools make it ideal for our project. EasyEDA's cloud-based platform allows for easy collaboration and access to our designs from any device. Overall, the software's balance of simplicity and functionality makes it the best choice for our project needs.

8.1.2 PCB Design Manufacturer

The next step after creating the PCB using our design software is to get it printed by a PCB manufacturing company. When selecting a PCB manufacturer, it's important we consider the advantages each company offers versus our needs for the project. Here's an overview of three manufacturers we considered to print our customized PCB, highlighting their key features and tradeoffs.

8.1.2.1 PCBWay

PCBWay[35] operates out of China, and they position themselves as a premium alternative to JLCPCB. Their prices are more expensive to manufacture customized PCB boards, as they emphasize quality control and more comprehensive service. Their assembly service particularly excels with sensitive components and complex designs. Manufacturing typically takes 2-3 days, and they offer extensive options for specialized materials and surface finishes.

8.1.2.2 JLCPCB

JLCPCB[36] is based in China, and stands out as the most cost-effective choice because pricing is significantly cheaper than other competitors. While

international shipping from China takes approximately 1-3 weeks, the cost savings often justify the wait. Their assembly service integrates with LCSC Electronics for component sourcing, offering a convenient solution for hard-to-solder parts. Standard manufacturing time is 1-2 days, and their user-friendly platform provides instant quotes and design rule checking.

8.1.2.3 OSH Park

OSH Park[37] is a US-based manufacturer. While their costs run higher per square inch of the board, they include free US shipping. They specialize in small-scale prototyping, allowing for smaller minimum orders than their competitors. Their signature purple solder mask and ENIG finish come standard, and while they don't offer assembly services, their quick domestic shipping and consistent quality make them an attractive option for reliability.

8.1.2.4 Conclusion

After evaluating these manufacturers, JLCPCB is the optimal choice for our project. Their significantly lower base pricing PCBs, makes them the most cost-effective option. While PCBWay offers higher quality control and OSH Park provides domestic convenience, JLCPCB's combination of quick manufacturing time, integrated assembly services, and substantial cost savings outweighs the longer international shipping times. Their established reputation and comprehensive component sourcing validate this selection as the most practical choice for our needs.

8.1.3 PCB Design Theory

During the process of designing our PCB for P.A.W.S., there are standards and methods that we will follow which will help transform the electronic circuit design made from our design software, into a functional and manufacturable physical board. PCB design involves a balance between arranging the components using traces, pads, and other elements to ensure that our circuit operates correctly. In addition to circuit functionality, PCB design also requires that we balance electrical performance with factors such as manufacturability, reliability, and efficiency.

The philosophy behind our PCB design lies in understanding the behavior of the electrical signals on the physical board and how layout decisions affect our circuit's performance. The placement of traces and components can introduce challenges like electrical noise, interference, and thermal issues, especially in high-frequency or sensitive areas of the circuits. Our PCB design will address these challenges by optimizing signal integrity, managing heat dissipation, and

ensuring stability, all while maintaining manufacturability following PCB design standard suggestions that meet our requirements. This section will dive more into these guidelines for P.A.W.S. PCB design.

8.1.3.1 Component Placement and Organization

Within our design for the P.A.W.S. PCB, distinct component placement will be crucial to ensure that the board efficiently handles the various high-power and sensitive elements like the Raspberry Pi, stepper motor drivers, and sensor interfaces. Having a specific placement of components will make certain that we are achieving optimal signal integrity, efficient power distribution, and effective thermal management. Starting with our largest and most critical components such as the Raspberry Pi module and motor control circuits, we will position these near the power input to reduce power loss and optimize thermal dissipation. For instance, placing the motor drivers close to the edge of the PCB will help with the heat dissipation, especially since they will handle significant current to control the motorized plexiglass doors. Additionally, organizing components into functional zones can help minimize interference. The sensors and any other analog detection circuitry will be kept physically distant from noisy digital components, like the Pi's GPIO connections, to reduce the risk of crosstalk that can affect sensor accuracy. Adhering to IPC-7351 [38], spacing guidelines which suggest maintaining a clearance of at least 0.1 inches between components during placement will help simplify assembly and reduce soldering issues, especially given the space constraints within our enclosure. Additionally, according to IPC-2221[39], a minimum spacing of 0.25 inches should be between the more high-power components to prevent thermal clustering.

8.1.3.2 Power and Ground Planes

For our P.A.W.S. PCB, the power distribution is essential since we're dealing with components that have varying power requirements (like the 5V Raspberry Pi and the 12V stepper motors). Implementing dedicated power and ground planes will stabilize voltage levels across the board, ensuring that motors and sensors receive reliable power. Using effective topology, regulators will distribute power directly to high-demand components like motor controllers, which will minimize voltage drops and noise. To handle the high currents required by the motors, we will use wider traces. Utilizing ground planes will also contribute signal integrity and assist in heat dissipation. In general, the ground planes will cover a large middle area of the board for optimization and to minimize noise interference.

8.1.3.3 Signal Routing and Trace Design

The P.A.W.S. system involves a mix of low-speed signals (from sensors) and potentially higher-speed data from the Raspberry Pi, especially when it's handling camera input for pet recognition. We will make sure to route sensitive analog signals away from noisy digital traces to reduce the risk of interference. To maintain signal integrity, we will also attempt to route traces directly, particularly for the sensor signals that control door actuation based on proximity detection. Traces should be kept as short as possible to reduce resistance and inductance, thereby minimizing potential signal degradation. Ensuring that power traces to the stepper motors are wider will help reduce resistance and prevent voltage drops that could cause unreliable door movement. For critical control signals, like those triggering motor actions, we will use controlled impedance traces to also help regulate the resistance. According to PCBway, keeping a minimum trace width of 0.006" prevents accidental shorts, which is effective for high-density design with both power and control circuits sharing the same board environment.

8.1.3.4 Thermal Management and Grid Spacing

Because of the enclosed design of P.A.W.S, thermal management is a priority, particularly since the stepper motors and the Raspberry Pi can generate considerable heat during prolonged operation. The design of thermal relief controls the rate at which heat moves through the PCB, preventing overheating by managing thermal conductivity. It can be advantageous to integrate thermal vias also known as through-holes beneath our high-power components, which will help transfer heat away from sensitive areas. Additionally, we will use grid spacing of at least 0.05 inches to help align components and simplify routing, but we will tighten this for high-density areas like the Raspberry Pi's GPIO connections.

8.1.3.5 Signal Integrity and Electromagnetic Interference (EMI) Considerations

Our project's reliance on sensors and potentially sensitive recognition systems means that maintaining signal integrity is important. Controlled impedance routing for high-speed signals from the Raspberry Pi (like I2C connections to sensors) can help prevent data errors. To minimize electromagnetic interference, we will utilize decoupling capacitors to ensure that the power lines to the motors are filtered, which will prevent motor switching noise from affecting the Pi or sensor operations. Separating the digital ground from the analog ground, especially for the sensor inputs, will also reduce EMI and protect sensitive signals from noise generated by the motors or other high-current components.

8.1.3.6 Design Verification

As P.A.W.S. involves various interconnected components and systems, design verification is significantly important. Running Design Rule Checks (DRC)[40] after placing components, routing power, and handling sensitive signal lines will help catch potential errors that could cause issues during assembly or operation. We will run a DRC after each major change, especially when adding high-power components like motor controllers, to catch errors early. For the PCB, ensuring consistent DRC checks as we adjust the layout for power and motor circuits can prevent costly rework before production. Performing these checks after every design stage will be particularly useful given the complexity of our system, where sensors, motors, and control circuitry need to function seamlessly together.

8.1.4 PCB Voltage Regulator

Designing a PCB to accommodate the TPS54JA20 voltage regulator requires careful attention to the layout considerations from the datasheet. Specifically, performance, thermal management, and electrical reliability. The TPS54JA20 operates up to high currents (12A) and frequencies (adjustable between 600kHz and 1MHz), making it essential to minimize electrical noise and heat dissipation. We will follow key design principles outlined in the datasheet to help achieve these goals.

The datasheet emphasizes the importance of using large, continuous copper planes for both the input power and ground connections. This helps minimize voltage drops due to resistance and reduces noise from high current flow. Placing the input capacitors close to the VIN and GND pins minimizes input ripple and noise. The ground plane should also act as a heatsink to aid thermal dissipation.

The SW (switch node) is a critical high-frequency node and must be kept as small as possible to reduce EMI (Electromagnetic Interference). The datasheet suggests a tight layout for the components connected to the SW pin, including the inductor and output capacitors, to minimize inductance and resistance. This also helps reduce radiated noise that could interfere with nearby circuits.

Proper thermal management for the TPS54JA20 is crucial for handling the heat generated during operation, especially under high-current loads. The datasheet recommends connecting the exposed thermal pad to a large copper area on the PCB through multiple thermal vias. This enhances heat dissipation by spreading it across the PCB layers.

High-frequency decoupling capacitors should be placed as close as possible to the VIN pin to ensure stable operation. The datasheet advises using low-ESR

ceramic capacitors for both input and output decoupling to maintain a clean power supply and minimize voltage ripple. Additionally, the feedback network should be carefully routed to avoid noise coupling, with the feedback trace kept short and away from the SW node. Below is the provided PCB layout from Texas Instruments for the TPS54JA20:

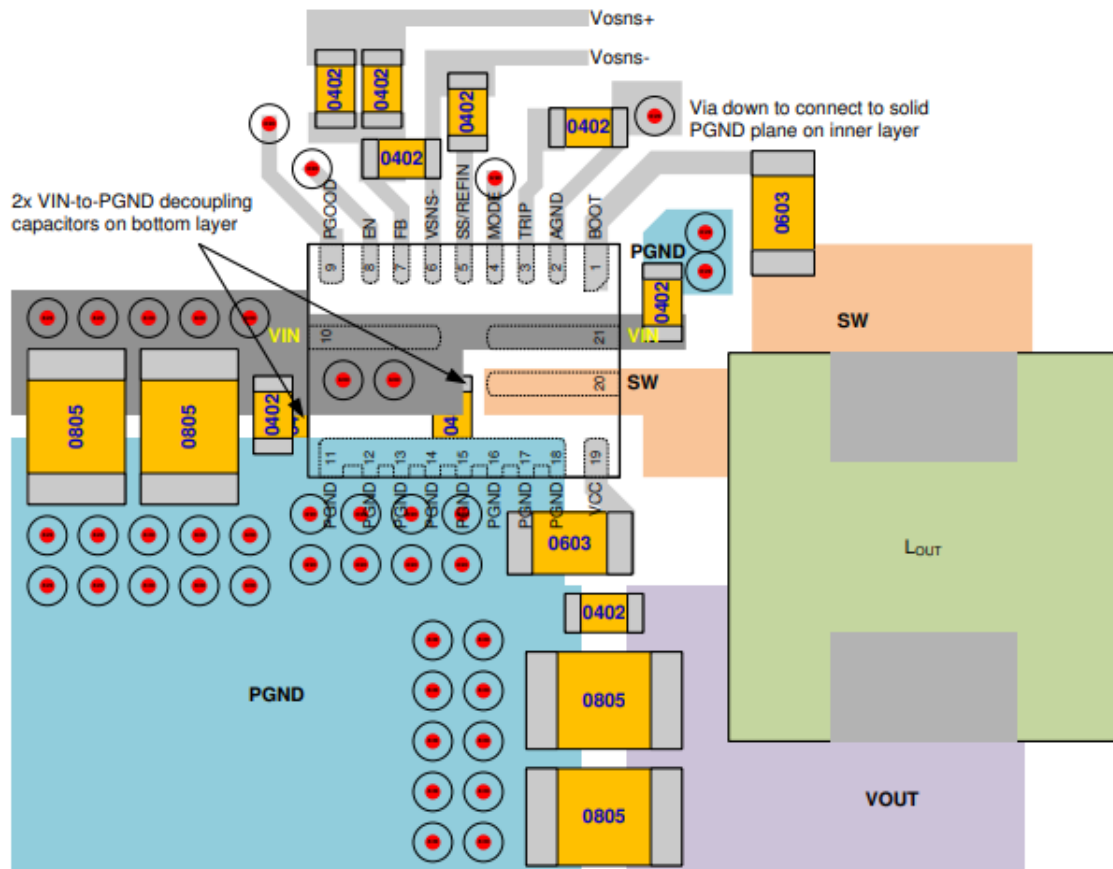


Figure (8.1) - PCB Voltage Regulator Layout (permission requested to use from Texas Instruments)

Chapter 9 - System Testing and Evaluation

This chapter will detail the testing and validation processes for both the hardware and software components of the AI-assisted litter box system. It will include performance evaluations to ensure each subsystem meets the project's specifications, such as the proximity sensor, break beam sensor, and door mechanism. The chapter will also cover the overall system integration, highlighting how the hardware and software work together to achieve seamless functionality. Finally, a plan for Senior Design 2 will be outlined, focusing on refining the prototype, addressing any identified issues, and preparing for final

implementation and demonstration. These steps will ensure the project is on track for successful completion.

9.1 Hardware Testing

9.1.1 Proximity sensor

The hardware testing process for our project involves thoroughly evaluating each subsystem to ensure reliable operation under real-world conditions. For the proximity sensor circuit, we adopted an existing design we found online, which includes an IR LED, a photodiode for detection, and a red LED to indicate when the circuit is active. While this circuit met our basic requirements during initial testing, further evaluation was necessary to optimize its performance for our specific application.

During testing, we encountered challenges such as misalignment between the IR LED and the photodiode, which could result in inconsistent detection. Additionally, environmental factors like ambient light or reflective surfaces near our set up caused some interference with the sensor's accuracy. Through trial and error, we addressed these issues by fine-tuning the placement and orientation of the components. To reduce interference, we tested various shielding techniques and adjusted the circuit's sensitivity using resistors. These refinements ensured that the sensor would work reliably in diverse conditions. We opted for adding an IR bandpass filter in front of our detector which reduced the interference immensely.

By systematically addressing these challenges during testing, we were able to enhance the circuit's accuracy and tailor it to our project's needs. This process not only improved the sensor's performance but also provided valuable insights for integrating it seamlessly with the rest of the system.

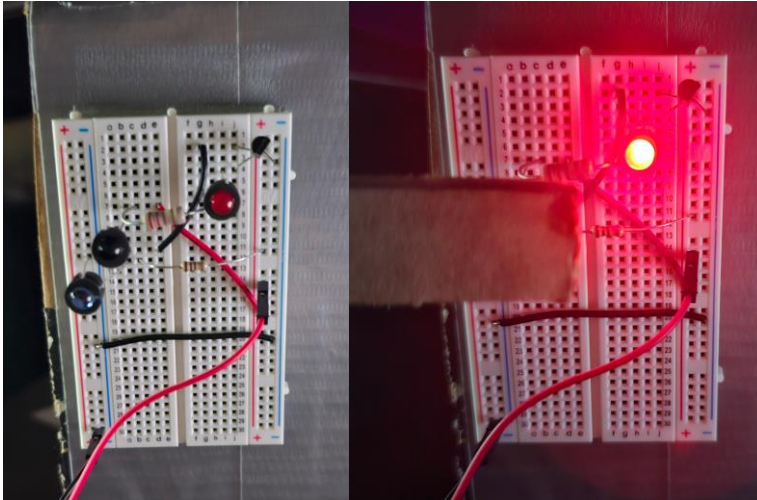


Figure (9.1) - Proximity sensor test, system turned off on the left. System on and with a cardboard piece placed in front of IR LED and photodetector to show the system is active.

9.1.2 Break-beam sensor

The hardware testing process for the break-beam sensor focused on ensuring reliable operation to detect when the cat enters the litter box and prevent the door from closing prematurely. The design consists of an IR LED emitter and a photodiode receiver positioned opposite each other across the entrance of the litter box. Initial testing demonstrated that the basic setup worked well, but some testing and adjustments were required to fine-tune its performance for our application.

One challenge we faced was ensuring precise alignment between the IR LED and the photodiode. Misalignment could result in the beam failing to connect, leading to false positives or missed detections. To address this, we developed a simple alignment fixture to hold both components securely in place during testing. Another potential issue was interference from ambient light, which could affect the photodiode's ability to distinguish the IR beam. To mitigate this, we experimented with adding an IR bandpass filter in front of the photodiode and tested different placement options to shield the sensor from external light sources.

Through extensive testing, we discovered that a lens was not necessary for the break beam sensor, as the IR LED and photodiode provided sufficient precision and alignment for our project's requirements. During initial trials, we evaluated whether a lens might be needed to focus or shape the IR beam for reliable detection. However, the natural directionality of the IR LED was adequate to project a consistent beam across the width of the litter box entrance, and the photodiode's sensitivity was sufficient to detect even slight interruptions without

additional focusing. By eliminating the need for a lens, we simplified the design, reduced potential alignment challenges, and minimized material costs while maintaining the sensor's reliability and effectiveness. This insight allowed us to streamline the system and focus on refining other aspects of the project.



Figure (9.2) - Break-beam sensor test, system-on(left). System with a cardboard piece placed in between of IR LED and photodetector showing the much dimmer red LED.

9.1.3 Door-Rail system

The testing process for the railing system, which enables the smooth movement of the automated door, revealed several challenges that required some problem-solving. One of the primary issues we faced was related to the programming and control of the stepper motor. Initial tests showed irregular movement and inconsistent response, which we traced back to errors in the stepper motor driver configuration. Through trial and error, we adjusted the step pulse timing and micro stepping settings in the driver to achieve smoother and more reliable motion.

Another challenge involved the mechanical coupler connecting the stepper motor to the threaded rod. The coupler we initially selected was slightly too small, leading to slippage and an unstable connection. To address this, we modified the design by carefully adding tape around the rod to fit securely while testing to ensure it could handle the torque generated by the motor. While this solution worked for initial testing, it highlighted a potential weakness in the system that will need further attention as we scale up testing.

Although we achieved functional operation of the railing system, we observed that the current motor lacks sufficient power to operate under higher loads or prolonged use. This has prompted us to explore alternative stepper motors and drivers that offer greater torque and efficiency. These adjustments will not only improve the system's durability but also ensure consistent performance as we integrate the railing system with the rest of the automated door design.

9.1.4 Voltage Regulators

The 3.3V and 5V voltage regulators were validated using simulation tools to ensure they meet the power requirements for our P.A.W.S. system. Specifically, we used WEBENCH Power Designer to design and test the circuits virtually before we do any physical implementation. This allowed us to simulate realistic conditions, including the expected load currents and expected input voltage of 12V. We also wanted to verify that the regulators would provide stable output voltages under all operating conditions. By confirming proper functionality in the simulation phase, we minimize the risk of power-related issues during integration.

For the 5V regulator, which powers the Raspberry Pi, the validation process focused on handling high peak currents of up to 5A without significant voltage drop. The tool simulated the interaction between the buck converter's switching components, such as the inductor and capacitors, to evaluate performance under load. Similarly, the 3.3V regulator, which powers the microcontroller and associated logic circuits, was tested for its ability to maintain its output, as these components can be sensitive to voltage fluctuations. The results in Figure 9.3 below demonstrates that our designs meet all requirements, providing confidence in their performance during the prototype phase.

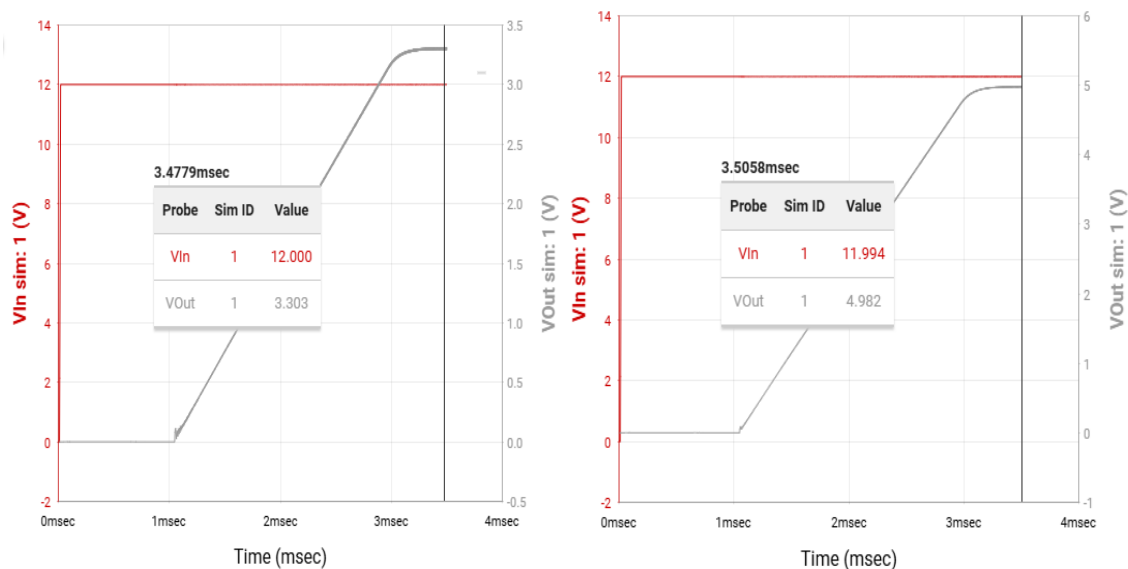


Figure (9.3) - 3.3V (L) and 5V (R) Voltage Regulator Simulations using WEBENCH Power Designer Tools

9.2 Software Testing

9.2.1 Computer Vision Algorithm

For the first iteration of the SD1 prototype, a small test case was created in Google Colab. The program does a basic inference from a single static image uploaded to a personal Google Drive. The image is a basic stock image of four animals, two cats and two dogs, running across a field in a 682x360 pixel format. The plan for this prototype is to utilize YOLOv10's algorithm to find two major factors: detection accuracy and inferencing time to completion. This process will be completed with every single weight file available to the model. The weights help the model more accurately detect what objects it sees in an image, however there is a large tradeoff. Larger weight files will take up more storage space, have a slower runtime, and take more processing resources to use. The largest weight files available are unlikely to run consistently or quickly enough on the Raspberry Pi but will still be tested for a baseline.



Figure (9.1) - Prototype testing image from Adobe Stock of two cats and two dogs running through a flower field. This image has confidence level bounding boxes from the medium model.

YOLOv10 includes six different compatible weight files: nano (N), small (S), medium (M), balanced (B), large (L), and extra-large (X). Above is the prototype testing image run with the medium weight file. This weight is designed for general purpose uses and offers a good balance between performance and computational requirements. We can see that the model is able to properly distinguish between the two cats and two dogs in the image, and can automatically put a bounding box around each. The numbers above are the

confidence level, expressed as a decimal value. For each of the dogs, the model is 87% and 81% sure that it is seeing a dog. Similarly, the model is 74% sure that it is seeing a cat for both cats. In the following table of weight testing on the image, each animal is labeled in order from left to right and grouped by animal type (cat or dog). Inference speed is marked in ms, and is the time it takes the model to make a single pass through the image and identify what it sees.

Table (9.1) - Table of different YOLO weight files and their effects on inference confidence level for each animal and overall inference speed in ms.

Weight	Dog 1	Dog 2	Cat 1	Cat 2	Inference speed (ms)
N	0.67	0.64	0.48*	0.56*	48.9
S	0.91	0.88	0.63*	0.70*	107.3
M	0.87	0.81	0.74	0.74	69.3
B	0.91	0.91	0.48**	0.44	48.3
L	0.90	0.88	0.63	0.59	51.1
X	0.83	0.92	0.82	0.83	66.1

As seen in the table above, identification confidence levels fluctuate wildly between weights. In some cases, a smaller compact weighting outperformed the larger more comprehensive weight. Cells marked with a single star (*) denote when the model detected an animal incorrectly. For this test, this only occurred during cat detection, with the model incorrectly identifying a cat as a dog. For the single cell marked with two stars (**), this denotes that the model identified the animal twice. In that case, the model identified the first cat in the image as both a cat and a dog. The confidence value of 0.48 in the table is taken from the cat identification level. While the confidence levels overall may be somewhat unreliable, they do still roughly follow the trend of higher weight levels having more accurate detection. For the full-scale project, is it likely that the model will use at least the medium weight file.

Inferencing speeds also varied quite heavily between weights. The small (S) weight file has a much larger outlier speed than the rest of the weights. This pattern continued even with testing this specific variation a total of three times.

On the opposite side, we also find that some larger weight files outperformed smaller ones in inferencing speed. The most notable is the balanced (B) weight file computing with the lowest time of all weights at 48.3ms.

Although the original plan for the P.A.W.S. detection system was to reach object identification accuracy of at least 90%, this no longer seems feasible based on prototype testing results. Specifications have been adjusted to a more reasonable 75% accuracy, however inference speed requirements have not been adjusted. As for which specific weight file to choose, further testing will be required on the physical Raspberry Pi device. Currently, however, it seems an easy choice to at least eliminate the nano and small versions, as they incorrectly identified both cats in an image with perfect lighting. While the Pi does have resource limitations, these limits are not so low as to require the compact N and S versions. On the other hand, it will need to be tested as to whether or not the Pi will be able to handle the large or even extra-large weights. If so, then it would make sense to use the most powerful one available as inference accuracy is the most important factor for the machine learning section of the project.

9.3 Overall System Integration

After testing each subsystem individually and verifying the results, the next step is to integrate piece by piece to eventually combine it all together into one working system for the final prototype and demo. The following section covers the main integration we expect to accomplish and our understanding of how these systems can communicate to accomplish our goal.

9.3.1 Integration of the Stepper Motor with the Sensors

The stepper motor is integrated with the system's sensors via a motor driver, enabling precise movement control based on sensor inputs. The proximity sensor and break beam sensor work in tandem to detect the cat's position, sending signals to the MCU. The MCU then processes these inputs and sends step commands to the motor driver, ensuring the motor operates at the correct horizontal speed. This integration allows for responsive and accurate adjustments throughout the testing process, such as opening or closing the door only when a verified cat is detected.

9.3.2 Integration of the Stepper Motor for the Horizontal Movement of the Plexiglass Door

The stepper motor drives the horizontal movement of the plexiglass door through a rail system with a threaded rod and drive nut mechanism. The motor's rotational

motion is converted into linear motion as the drive nut travels along the threaded rod. This design ensures smooth and controlled movement, while the rail system provides stability and alignment. The integration is critical for the door's functionality, as it must operate reliably to prevent interference with the sensors and maintain safety for the pet.

9.3.3 Integration of the Raspberry Pi and Software with the Camera, Proximity Sensor, and MCU

The Raspberry Pi serves as the central processing unit for advanced functions, including facial recognition via the camera. The software component, leveraging the YOLOv10 algorithm for object detection, integrates directly with the proximity sensor and motor system to enable automated functionality. Once the proximity sensor detects motion near the door, the Raspberry Pi activates the camera to capture an image of the subject. This image is then processed by the YOLOv10 model running on the Raspberry Pi, which identifies whether the detected object is the authorized cat. If the model verifies the cat with sufficient confidence, a command is sent to the microcontroller to activate the motor driver, opening the plexiglass door. This integration gives us confidence that the door operates only for verified entries, reducing false activations.

9.4 Plan for SD2

Our plan of action for the next semester focuses on finalizing the design, addressing unresolved challenges, and preparing for the completion and demonstration of the AI-assisted litter box system. The first priority will be refining the hardware, particularly the railing system and sensor components. We will research and integrate a more powerful stepper motor and an appropriately sized coupler to ensure reliable operation of the automated door. Additionally, we will revisit the proximity sensor and break beam sensor circuits to optimize their performance further and ensure seamless integration with the overall system.

On the software side, we will focus on debugging and improving the control algorithms for the stepper motor and sensors, ensuring smooth communication between the Raspberry Pi and MSP430 microcontroller. This includes refining the timing and synchronization of the door operation with the sensor inputs. A key focus will also be ensuring that our machine learning algorithms are working accurately to distinguish between a cat and a dog. This involves fine-tuning the IR camera's data processing and retraining the model as needed to minimize false positives and negatives. By improving the accuracy of this detection, we ensure that the system only opens the door for the intended user—the cat—further enhancing the functionality and reliability of the design.

Once individual subsystems are finalized, we will shift to comprehensive system integration and testing. This phase will involve running extended tests to evaluate the system's performance under realistic conditions, identifying any remaining issues, and making adjustments as needed. Simultaneously, we will work on the physical assembly of the litter box system, ensuring a polished, user-friendly design for the final demonstration. By following this structured plan, we aim to complete the project successfully and deliver a functional, innovative solution for mixed-pet households.

Chapter 10 - Administrative Content

This chapter discusses the financing, work distribution, and milestones of the project.

10.1 Marketing

This subsection discusses the marketing of the project.

10.1.1 Budget and Financing

This subsection discusses the finances of the project.

Table (10.1) - Budget breakdown and financing details. Does not factor in delivery costs and taxes.

Component(s)	Unit Cost	Total
Fully-enclosed rectangular structure	\$74.99	\$74.99 (1)
IR Imaging camera	\$25.99	\$25.99 (1)
Plexiglass sheets	\$2.00	\$10.99 (5)
Motorized rail-system (all parts included)	\$35.00	\$35.99 (1)
LCD display	\$35.99	\$35.99 (1)
IR LED	\$ 0.32	\$ 7.95 (25)
Photodetector	\$0.27	\$5.49 (20)

Velostat pressure sensitive sheet	\$4.99	\$9.99 (2)
Misc. Hardware (screws, wiring, etc.)	\$14.99	\$14.99 (1)
Single-Board Computer (Raspberry Pi)	\$80.00	\$80.99 (1)
Microcontroller	\$15.00	\$15.99 (1)
Custom PCB	\$12.00	\$80.99 (6)
Overall Total (approximately)		\$400.34

10.2 Work Distribution

This following subsection discusses the work distribution between the different members of the team.

Table (10.2) - Team member work distribution and responsibilities.

Photonics Engineering	Responsibilities
Luana Capel Secondary: Christian Williams	Sensor Design and Implementation
	Enclosure Design
	Administrative Documentation
	Project Manager
Computer Engineering	Responsibilities

Kinza Rashid Secondary: Luana Capel	Mobile App Design
	Enclosure 3D Modeling and Development
	PCB Fabrication
	App Data Management
Electrical Engineering	Responsibilities
Jeffrey Sotello Secondary: Kinza Rashid	PCB Design
	PCB Fabrication
	Power Supply Research and Implementation
	Motor Configuration
Computer Engineering	Responsibilities
Christian Williams Secondary: Jeffrey Sotello	Embedded Software Design
	Software Management
	Camera Implementation
	UART Configuration

10.3 Project Milestones

This following subsection presents the milestones of the project.

Table (10.3) - Senior Design 1 project milestones.

SD1 Milestones - Project Definition, Research, and Design				
Start Date	Due Date	Target Slack Time (days)	Task	Description
8/20/2024	8/22/2024	0	Group-forming	Members assembled as Group 9: Luana Capel (PSE), Kinza Rashid (CPE), Jeffrey Sotello (EE), Christian Williams (CpE)
8/23/2024	9/1/2024	0	Project discussion and brainstorming	Several virtual and in-person meetings to discuss project details and ideas.
8/25/2024	9/6/2024	2	D&C document, draft	Several virtual and in-person meetings to work on drafting Chapters 2 and 10 of Final Report.
9/1/2024	9/25/2024	1	Selection of components	Several virtual meetings and

			(proposed)	check-ins to pick components and start drafting the Bill of Materials.
9/11/2024	9/27/2024	1	D&C document, revised	Several virtual and in-person meetings to work on finalizing Chapters 2 and 10 of Final Report. Possible addition of Chapter 3.
9/26/2024	10/10/2024	1	Selection of components (finalized)	Meeting(s) w/ Dr. Weeks to verify selected project components.
10/11/2024	10/17/2024	0	Order prototype components	Order and collect all components necessary for the prototype.
9/28/2024	10/25/2024	3	60-Page Report, draft	Several virtual and in-person meetings to work on

				drafting the 60-Page Report.
10/11/2024	10/17/2024	0	Order prototype components	Order and collect all components necessary for building the prototype.
10/30/2024	11/8/2024	1	60-Page Report, revised	Several virtual and in-person meetings to work on finalizing the 60-page Report.
10/31/2024	11/26/2024	2	Build prototype	Start building on breadboard(s) , testing each component before integrating together for the final prototype.
11/9/2024	11/26/2024	3	Final report	Several virtual and in-person meetings to complete the 120-page Final Report.

Table (10.4) - Senior Design 2 projected milestones, subject to change.

SD2 Milestones				
Start Date	Due Date	Target Slack Time (days)	Task	Description
1/6/2025	1/20/2025	5	Buy remaining parts	Compile list of all missing components needed to start building full prototype
1/20/2025	3/3/2025	5	Start Assembling	Begin assembling final prototype
3/3/2025	3/7/2025	5	First Round Test	After finishing assembling, begin testing
3/10/2025	3/14/2025	5	Second Round Test	Plan for another round of tests
TBD	TBD	-	Demo	Prepare for optical demo
4/17/2025	4/17/2025	0	Showcase	Have the final working product completed

Chapter 11 - Conclusion

The idea for our senior design project was to create a smarter and more efficient solution for something that happens in homes with different pets. Mixed-pet households often have trouble finding a safe and reliable way for only one pet to get to the litter box. We thought this common problem needed a new and better solution. Because of this challenge, we wanted to create and test an AI-powered litter box. This won't be an ordinary litter box. We'll use special sensors and smart automation so that only the cat can get in. Other pets, especially dogs, will be kept out. This project brings together engineering, automation, and design focused on how users think. We want to really understand how we can help people and make something useful and smart.

The importance of this project is that it addresses a common problem and shows basic engineering principles applied in a clear way. Households with different kinds of pets usually must deal with problems like keeping the litter box safe from the other pets that live there. This is a big concern for pet hygiene and safety. We're creating a dependable and easy-to-use access system. This system uses IR sensors to detect when something is nearby and has an AI object detection that only lets the correct animal inside, that being the cat. The door, powered by a stepper motor, opens softly and quietly. Also, this project is a great chance to turn our textbook engineering ideas into a real-world challenge. This aligns perfectly with the goal of this course, which is to strengthen our skills with optical sensors, motor controls, and putting systems together.

Throughout this semester, we have made significant progress in realizing our goals. Starting with initial brainstorming sessions, we refined our design to include key components such as the proximity and break beam sensors. These sensors, combined with the use of IR LEDs, photodiodes, and carefully selected optical lenses, form the core of our system's detection mechanism. We also introduced enhancements such as an IR bandpass filter to improve signal accuracy and reduce environmental interference, ensuring robust performance in real-world conditions.

To further enhance safety and usability, we implemented a pressure pad system to go inside the enclosure. This system detects weight changes near the entrance of the door to confirm the presence of a cat, providing an additional layer of safety as it enters and a means of exit when the cat wishes to leave.

In addition to the sensor design, we successfully implemented a stepper motor mechanism to operate the plexiglass access door, which moves smoothly across a threaded rod. This setup demonstrated the potential for precise and reliable operation, laying the groundwork for full integration with the AI identification

system next semester. We also completed detailed schematics and circuit designs for all our subsystems, which are ready for testing and refinement in the next phase.

An early prototype of the computer vision AI object identification and inference system was successfully set up. Currently, the YOLOv10 model can only run using single static images through Google Colab. For Senior Design II, the plan is to build off this prototype to first begin testing on the actual Raspberry Pi 5 itself, then to work up to running inferences on real-time video from the connected camera module.

Looking ahead to next semester, our plan focuses on integrating the components into a fully functional prototype. This includes finalizing the AI-based identification system to differentiate cats from dogs, optimizing the motor control mechanism for smooth door operation, and testing the entire system for durability and reliability. Additionally, we aim to enhance the system's user interface, ensuring ease of setup and operation for pet owners. Testing in realistic environments will be a priority to confirm the system's effectiveness and adjust as needed.

We are proud of the progress we have made so far and are confident in the foundation we have built for this project. By overcoming challenges and iterating on our designs, we have gained valuable insights and developed a solid framework for achieving our goal. This semester's work represents a crucial step forward, and we are excited to continue refining and enhancing our design to deliver a fully operational prototype.

In conclusion, our AI-assisted litter box system represents a meaningful contribution to addressing a practical problem in pet care. This project not only applies engineering concepts but also emphasizes innovation and user convenience. As we move into the next phase, we remain committed to delivering a solution that is both effective and user-friendly, ensuring that our final product meets the needs of pet owners while showcasing our skills and dedication as future engineers.

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52Fgeneral%252Fdocs%252Fsuppproductinfo.tsp%253FdistId%253D10%
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Appendix B - Datasheets

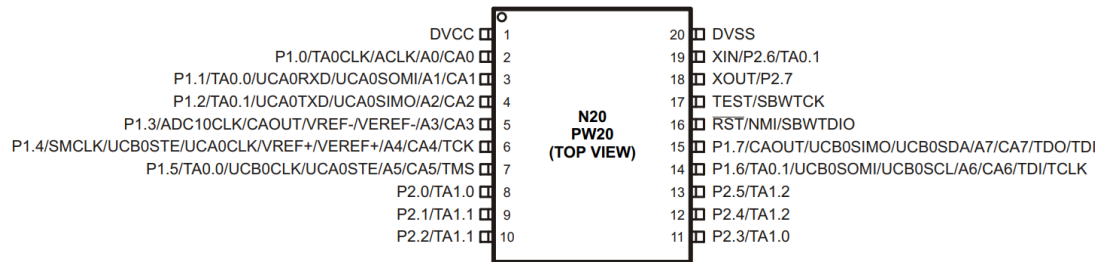


Figure (B.1) - Device Pinout, MSP430G2x13 and MSP430G2x53, 20-Pin Devices, TSSOP and PDIP [65]

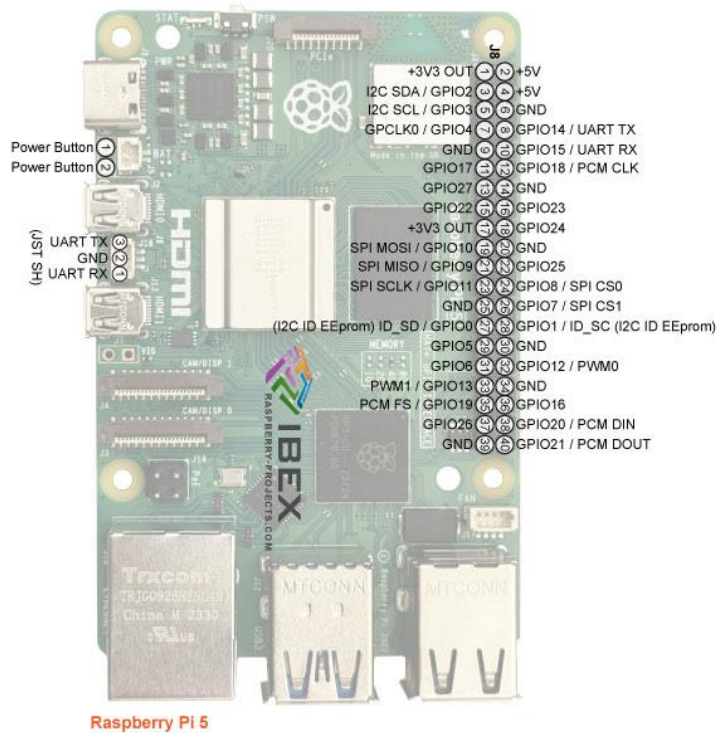


Figure (B.2) - Device Pinout, Raspberry Pi 5, 40-Pin GPIO Header [66]

Appendix C - Resources and Links

Image resources:

- P.A.W.S. logo by Patrick King (Software used: Photoshop)
- P.A.W.S. design concept and state sequence diagram by Kinza Rashid (Software used: Freeform)
- Mobile Application Design by Christian Williams (Software used: Photopea)
 - “Saved Pictures” cat images taken by Christian Williams
- 3D P.A.W.S. prototype concept by Kinza Rashid (Software used: Fusion 360)
- Hardware Block Diagram by Kinza Rashid (Software used: draw.io)
- Software Block Diagram by Christian Williams (Software used: draw.io)

Product Links:

<https://meowspace.biz/shop/>

<https://www.chewy.com/surefeed-microchip-small-dog-cat/dp/157144>

<https://elonics.org/infrared-ir-proximity-obstacle-sensor-using-lm-358/>

Declaration: We hereby declare that we have not copied more than 7 pages from the Large Language Model (LLM). We have utilized LLM for outlining, checking grammar, and summarizing purposes.