# P.A.W.S.

## **P**rotected **A**ccess for **W**hiskered **S**ubjects: AI-Assisted Litter Box System


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# Chapter 1 - Executive Summary

Our senior design project has focused on an issue faced by many households with both cats and dogs: How do you keep a dog out of a cat's litter box? Dogs are often attracted to cat litter boxes and can make a real mess if they should happen to get inside. Our solution combines AI recognition technology, infrared sensors, and a motorized door to create a secure, selective access system that allows only the cat to 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.

All in all, our litter box system with assisted AI represents a practical, effective, and scalable 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. According to PetMD, this is a very common practice among canines. 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.

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. 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.
- Manual override switch.

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

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.
- A cat paw-pad scanner.
- Integrated weight tracking.
- Liquid crystal sheet attached to plexiglass door.

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.
- 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:

- Allow the owner to save snapshots locally.
- A cat paw-pad scanner.
- Integrated weight tracking.
- 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.

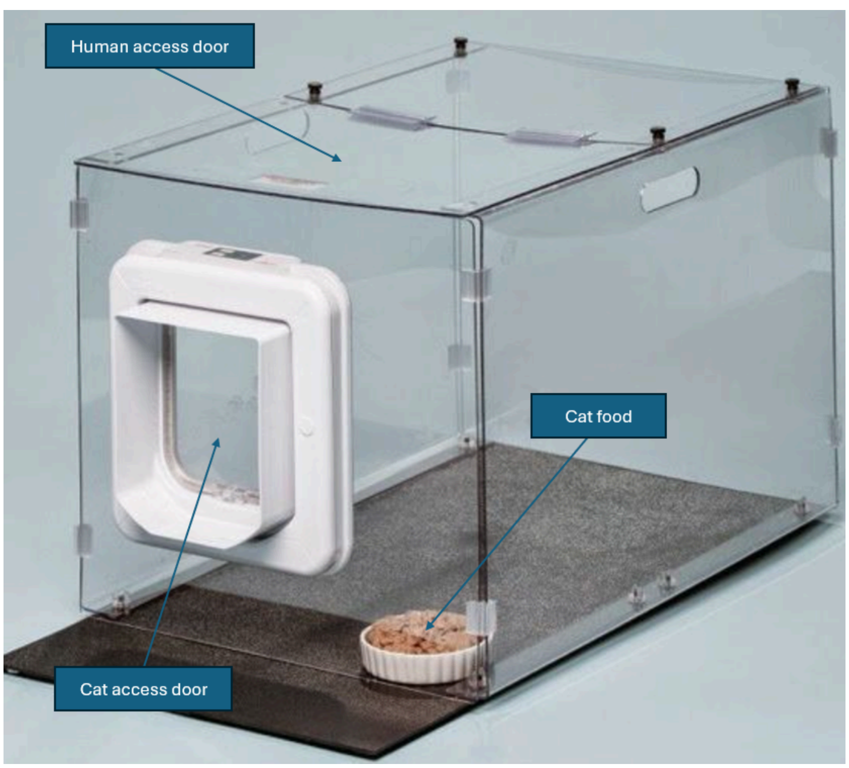
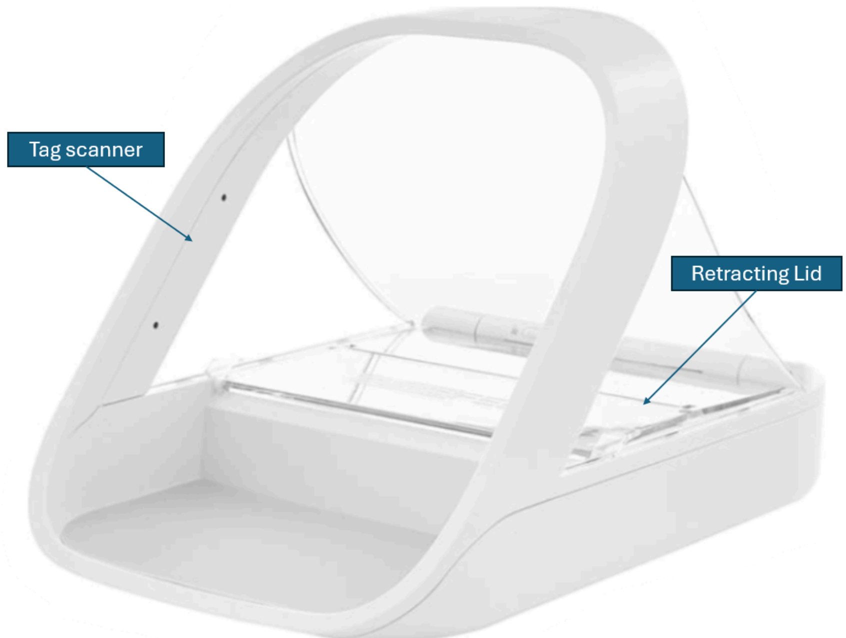


Figure (2.2) - SureFeed Microchip Small Dog & Cat Feeder.




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.

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’. | ≥ 3' x 2' x 2' feet |
| The system's plexiglass door shall have a maximum dimension of 16” x 16”. | ≤ 16" x 16" 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 | ≥ 90% |
| | 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° |
| Velostat | Pressure | 1lb minimum |

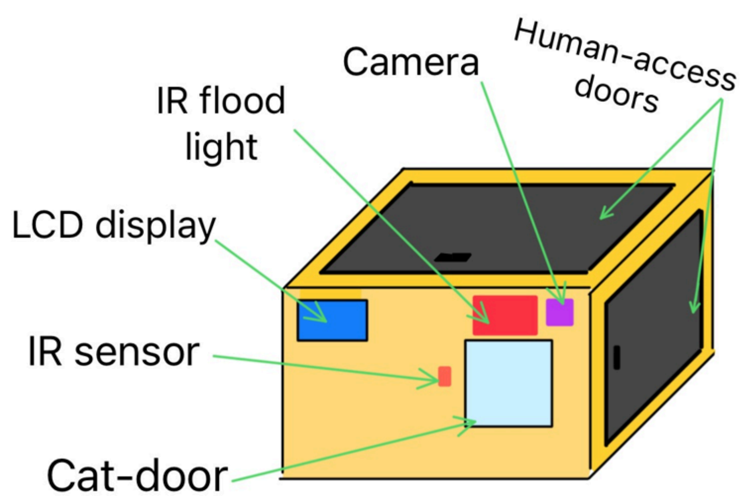
## 2.6 Prototype Illustrations

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 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.

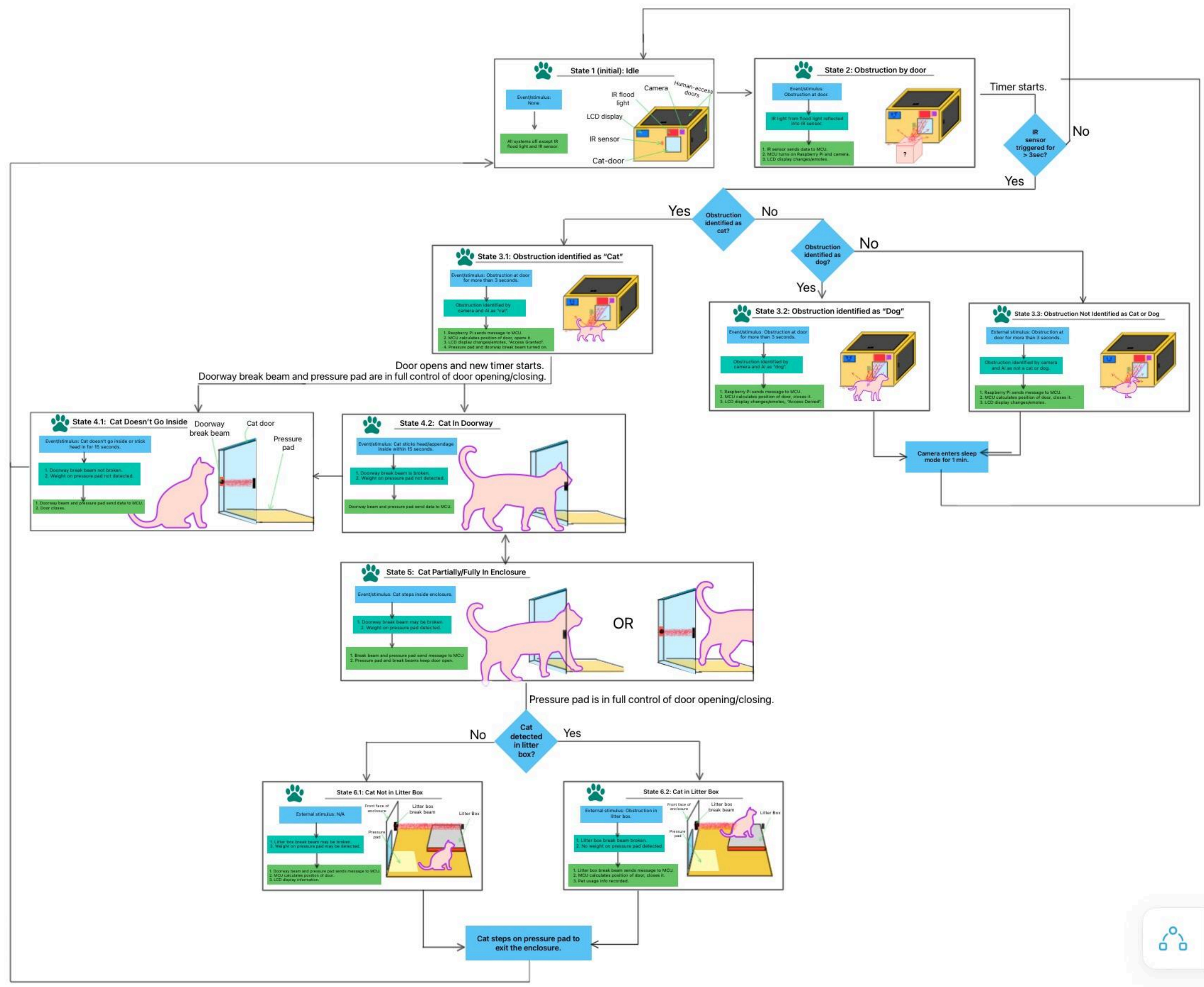
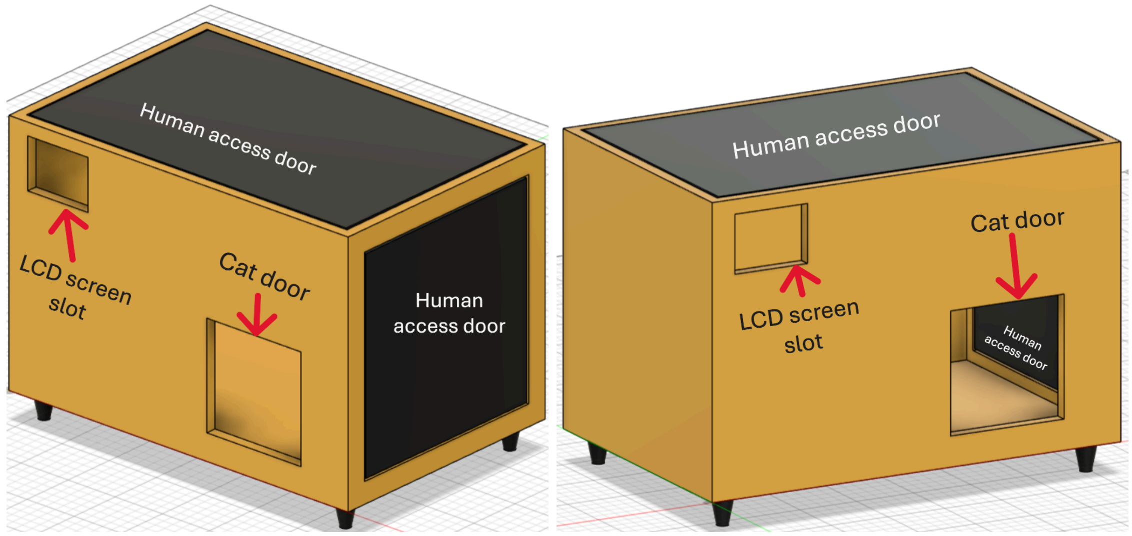



Table (2.3) - The envisioned physical system's states broken down into five key states and their interactions and/or interactions.

| Key States | Interactions/Transitions |
|---|---|
| 1. Initial State (Idle) | • System is in low power mode<br>• Only IR proximity sensor is actively monitoring<br>• Waits for objects within 1 foot of door |
| 2. Detection & Identification | • IR sensor triggers camera module |

| | |
|---|---|
| | • Computer vision system identifies object<br>• Decision making:<br>  ○ If cat: proceeds to door opening<br>  ○ If non-cat: returns to idle state |
| 3. Safety Mechanisms | • Multiple redundant sensors ensure safe operation:<br>  ○ IR break beam in doorway<br>  ○ Pressure pad inside enclosure<br>  ○ Timer system for automated closing<br>• Any sensor activation keeps door open<br>• Timer resets when sensors are triggered |
| 4. Entry Sequence | • Door opens upon cat identification<br>• Stays open while:<br>  ○ Break beam is interrupted<br>  ○ Pressure pad is activated<br>  ○ Timer hasn't expired |
| 5. Exit Sequence | • Similar to entry but reversed<br>• Pressure pad activation triggers door opening<br>• Door remains open until cat completely exits<br>• 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) - Initial 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 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.

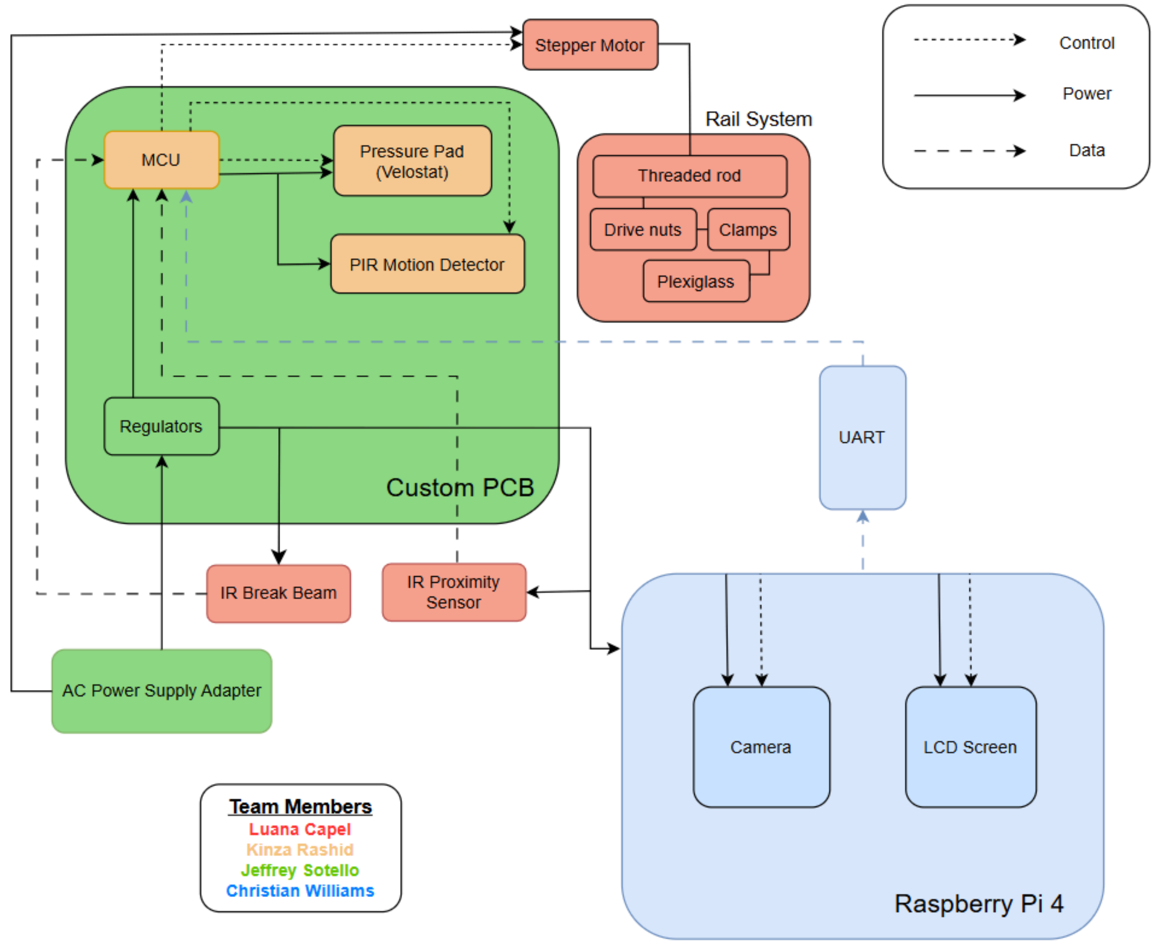
The mobile app will communicate with the P.A.W.S. enclosure through the Raspberry Pi's integrated WIFI capability. If not currently being interacted with, the Pi should stay in low-power mode in order to maximize the overall battery life. Saved pictures and activity logs are stored locally on the user's 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 MCU (MSP430) controls and coordinates the peripherals in the system, such as the LCD screen, IR sensor, stepper motor, and the Raspberry Pi 4 board via UART communication. It features LCD control, timers, and UART, all necessary for the project implementation. The LCD display will interface with the MSP430 chip to present information to the user, timers will be used for the motor control, and the UART communication system will be used to exchange important data between the Raspberry Pi SBC and the MCU. The regulators regulate the power supply going to different parts of the system, ensuring the appropriate voltages for the MSP430 MCU, the Raspberry PI SBC, LCD Screen, stepper motor, flood light, and sensors.

The PCB houses the MCU, LCD Screen, and regulators. The AC power supply converter transformer provides power to the entire system. The infrared flood light is powered directly by the AC supply. A signal is added to the flood light and modulated to be sensed by the IR sensor. The camera module is a wide-lens IR camera used for animal identification. The photosensor will be used as a break-beam sensor to add an extra layer of safety to detect obstructing objects in the door's path. The pressure sensitive conductive sheet is used to detect weight on the inside of the door, forcing the door open until the weight is removed. The tasks of animal identification and processing sensors' data are delegated to the Raspberry Pi, while the MCU on the PCB will configure and coordinate motor control, the LCD control, and the IR sensor data. So when the correct conditions arise (determined after processing the camera and sensor data), the Raspberry Pi will send a message to the MCU via UART, which will then activate the motor for the door opening/closing.

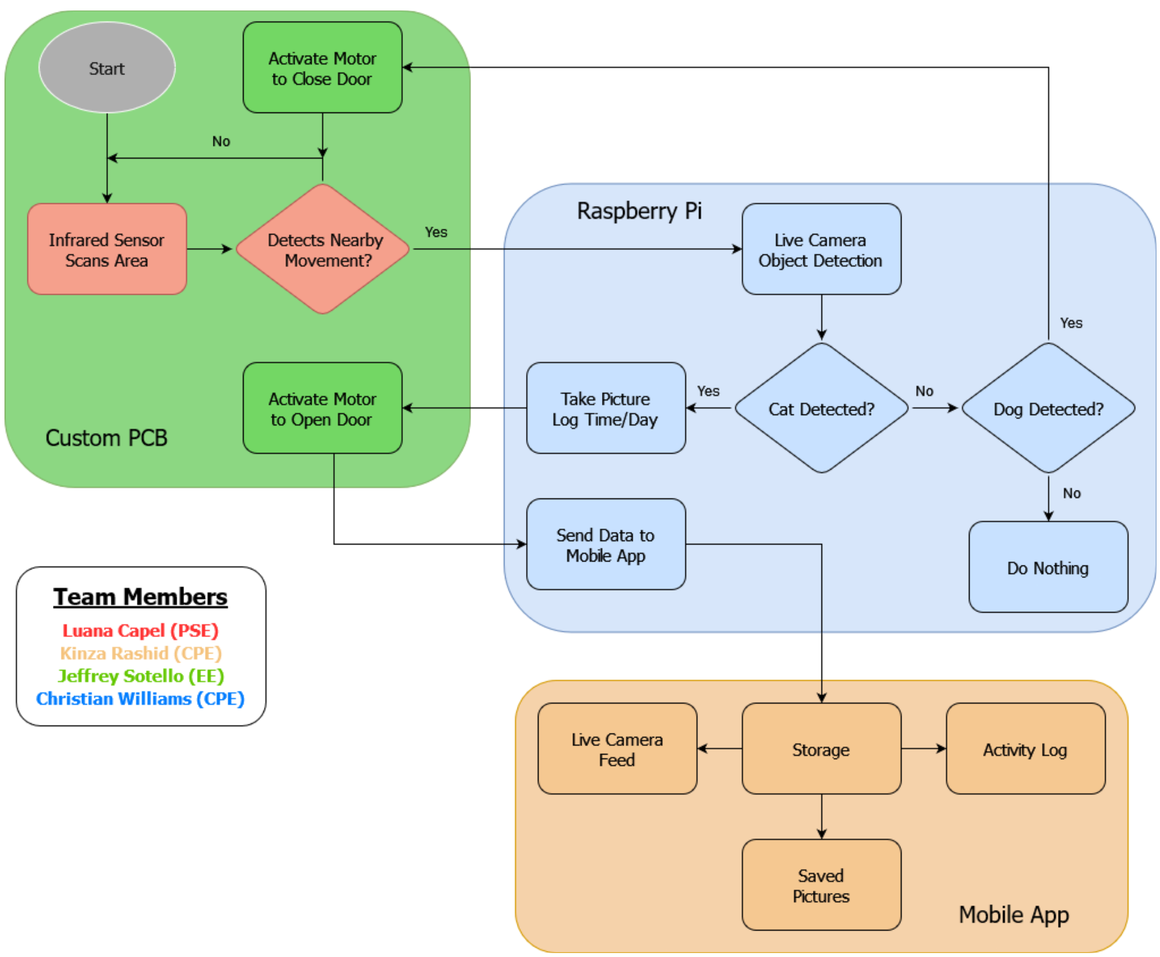
Figure (2.7) - Hardware Block Diagram.




## 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

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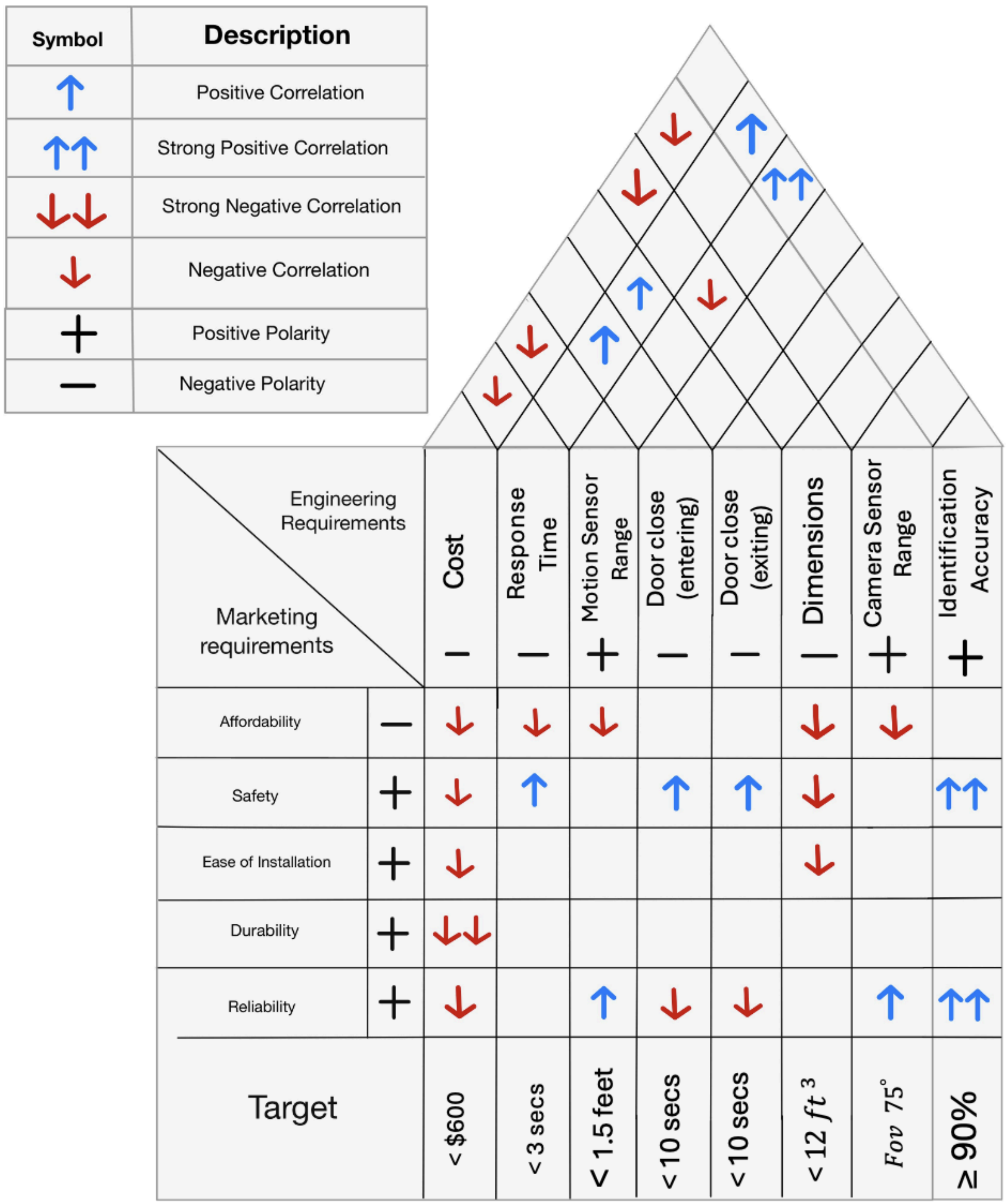
## 2.10 House of Quality

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, a pressure pad system, and a PIR motion sensor.

#### 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 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 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.

### 3.1.1.4 Comparative Analysis

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

For the integrated system control project, the microcontroller was selected as the primary logic chip. Using this processing technology for this integrated system control project provides the optimal balance of performance, energy efficiency, cost-effectiveness, and ease of development. The project's requirements, including motor control, IR radiation optics systems management, pressure pad system integration, and PIR motion sensor monitoring, fall within the capabilities of modern microcontrollers. The sequential nature of these tasks aligns well with the architecture and the low cost and low power consumption are significant advantages.

The economical nature of the microcontroller is further enhanced by the integration of necessary peripherals within a single chip, overall reducing system costs and simplifying the PCB design. The ability to program microcontrollers using high-level languages also reduces development time and allows for easier maintenance and updates. Additionally, the compact size of microcontrollers aligns with the project's need for a discrete form factor, due to the . This allows for a more compact overall system design, which can be crucial in space-constrained applications. Modern microcontrollers come with a wide range of integrated peripherals, including PWM generators for motor control, ADCs for sensor inputs, and various communication interfaces. This integration reduces the need for external components, further simplifying the system design.

## 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

### 3.1.3 Motion Detection …

### 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.

## 3.1.4.2 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.

### 3.1.4.2.1 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.

### 3.1.4.2.2 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.

## 3.1.4.3 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.

### 3.1.4.3.1 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.

#### 3.1.4.3.2 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.

#### 3.1.4.3.3 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.

#### 3.1.4.3.4 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.

### 3.1.4.4 Comparison and Selection

Given the project's requirements and constraints, the focus is narrowed to DC-compatible motors: BLDC motors, servo motors, and stepper motors. Each of these technologies offers unique advantages and challenges for the application.

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.

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 could limit the door's travel range. Additionally, the integrated feedback mechanisms –while beneficial for some applications– add unnecessary complexity to the system.

### 3.1.4.5 Conclusion

After careful consideration, it was determined that a stepper motor will offer the best balance of features for the automated door-opening subsystem. 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.

### 3.1.4.6 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. The lightweight nature of the plexiglass door means that the stepper motor's inherent torque capabilities are adequate without amplification. The mechanical design minimizes friction, eliminating the need for the additional torque a gearbox would provide. The stepper motor's native step resolution is sufficient for controlling the door's position without the need for further reduction. Omitting the gearbox keeps the system simpler and more cost-effective, aligning with fundamental project goals. A compact design is preferable, and adding a gearbox would increase the overall size of the motor assembly.

### 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 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, easy integration into the enclosure design is allowed by the wide range of available 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.

| Aspect | Rechargeable Battery | Outlet |
|---|---|---|
| Cost | Moderate | Low |
| Maintenance | High | Low |
| Efficiency | Moderate | High |
| Reliability | Moderate | High |
| Location Convenience | High | Moderate |

#### 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

There are several advantages to using infrared (IR) light for building a proximity sensor, 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.

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.

The fact that infrared light can penetrate certain materials that visible light cannot gives the sensor even more possible uses. 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. 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. In applications where pets are likely to be in the path of the emitted light, an IR LED is a far safer bet. From a purely economic standpoint, IR LEDs are typically much cheaper than laser diodes.

When it comes to performance, infrared 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.

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.

### 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. 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.

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.

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.

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.

Choosing a lens for an infrared application involves picking materials that can transmit infrared light effectively. Some choices include germanium, which is often used in optics, and silicon, which can also be used to make very high-quality infrared optics. Lenses are often coated, and for infrared applications, you want to make sure the coating is appropriate for the wavelength you're using.

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 setup becomes more dependable at greater distances. If a lens is placed in front of the LED, the infrared light can be more accurately projected into a narrow beam. With this configuration, the detector and lens combination can more reliably detect when the beam path is unobstructed.

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

To sum up, the selection of a plano-convex lens for both a proximity sensor and a break beam sensor yields clear benefits concerning light concentration and system efficacy. The infrared light emitted from the IR LED is collimated into a more narrow, directional beam, vastly improving the sensor's range and accuracy. In both applications, this concentrated light makes the system more effective at what it's supposed to do: detect the presence of an object either nearby or interrupting a beam of light.

Furthermore, a photodiode paired with a simple plano-convex lens allows for more effective and more sensitive projections of a detected infrared light beam. This is because the lens better collimates the projected light. And the lens better focuses the reflected light back to the photodiode. The configuration with the projection of a beam and the detecting of return light in either a close-range or broken beam setup can both be made effective and reliable using a plano-convex lens combined with a photodiode.

### 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.

| Aspect | Linear Regulators | Switching Regulators | | |
|---|---|---|---|---|
| | | Buck | Boost | Buck-Boost |
| Voltage Output | Step-Down | Step-Down | Step-Up | Step-up or Step-Down |
| Heat | High | Low | Low | Low |
| Efficiency | Moderate | High | High | High |
| Cost | Low | Moderate | Moderate | High |

## 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 ($I^2C$), 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 ($I^2C$)

$I^2C$ represents a more sophisticated protocol designed for short-distance communication between integrated circuits. It utilizes a two-wire interface for bi-directional communication.

The $I^2C$ 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.

$I^2C$ 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

$I^2C$ 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, $I^2C$ 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 $I^2C$. 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 $I^2C$. 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 operate in a low-power mode while inactive to save on battery life. 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 quick detection times. For this project, the most important factors to consider should be the cost and power consumption.

### 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. One of the important considerations with the SBC, as mentioned earlier, is the power constraints. 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. One of the objectives of P.A.W.S. is for the enclosure to be able to run without recharging for long periods of time. 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 power management.

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 singular Raspberry Pi 5 model.

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.

### 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. One of the biggest deciding factors for this project is if the significant increase in processing power is worth the significant increase in power consumption.

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. Despite its power, the Nano requires a minimum budget of at least $105 for a used board from a third-party reseller.

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.

The P.A.W.S. project does not necessarily require the huge amount of processing power that these components would provide. The cheaper, more efficient options like the Raspberry Pis or BeagleBone are easily powerful enough to handle the AI object detection and classification tasks. While all specs will be compared, the most important to consider remain the cost, power consumption, and RAM capacity.

Table (3.X) - Single-board computer component comparisons.

| Component | Raspberry Pi 4 | Raspberry Pi 5 | Coral Dev Board Mini | Beagle Bone 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 power 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 now 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 a similar RAM version. Ultimately, the group has decided that the P.A.W.S. enclosure will use the Raspberry Pi 5 4GB RAM version. This version is powerful enough to handle any AI-related tasks while also being cost efficient for the project's budget.

### 3.2.2 Optical Parts Selection

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

## 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 near-object detection is needed. This infrared laser diode with an 850 nm wavelength has plenty of power for good efficiency in near-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.

## 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 not only boosts the module's reliability in outdoor or well-lit conditions but also makes it particularly well-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 petite 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.

## 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 budget friendly.

Table (3.X) - 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<br>5mm diameter | 35mm x 5mm<br>5 mm diameter | 35 mm x 5 mm<br>5mm diameter |
| Range | 1~30 meters | - | - |

| | | | |
|---|---|---|---|
| Approx. Cost (per unit) | ~ $30 | ~$0.45 | ~$0.27 |

# 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.

## 4.2 Practical Constraints

This subsection discusses the practical constraints on the team when developing this project.

# 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.

The models that arose from this innovation—most notably GPT (Generative Pre-trained Transformer)—developed by OpenAI, revolutionized language generation by performing unsupervised learning on huge amounts of data. Over time, more advanced versions of these models—like GPT-2, GPT-3, and GPT-4—were released and demonstrated amazing abilities at understanding and producing text. 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 and changed the game for tasks like search and translation. In 2023, Anthropic introduced Claude, 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.

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.

### 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.

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 be using it at all? Why or why not?

You might think you can trust it, but you can't, and here's why. 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 legitimate piece of work in your 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.

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. It is not a revolutionary tool because it lacks the most basic and necessary human-like intelligence and "understanding" needed to produce high-caliber academic research. If anything, it is a more sophisticated Google Search. And what it really does, or should be done with it, is provide a pathway to better academic practices and a more conscious way to use the Internet. Moreover, using LLMs in a research context could impede the development of certain essential skills, such as critical thinking. Simply thinking that knowing what something is/does is not equivalent to understanding and doing yourself. Ethical issues are also a huge concern when utilizing AI generated content, specifically if one tries to pass it as their own.

### 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.

# 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 | $19.99 | $19.99 (1) |
| Plexiglass door | $19.99 | $19.99 (1) |
| Motorized rail-system | $39.99 | $39.99 (1) |
| Battery | $9.99 | $9.99 (1) |
| LCD display | $14.99 | $14.99 (1) |
| IR flood light | $19.99 | $19.99 (1) |
| Photosensor | $4.99 | $9.98 (2) |
| Velostat pressure sensitive sheet | $4.99 | $4.99 (1) |
| Misc. Hardware (screws, wiring, etc.) | $14.99 | $14.99 (1) |
| Single-Board Computer (Raspberry Pi) | $44.99 | $44.99 (1) |
| Microcontroller | $9.99 | $9.99 (1) |
| Custom PCB | $9.99 | $9.99 (1) |
| Overall Total | | $299.85 |

## 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<br>Secondary: Christian Williams | Sensor Design and Implementation |
| | Enclosure Design |
| | Administrative Documentation |
| | Project Manager |
| **Computer Engineering** | **Responsibilities** |
| Kinza Rashid<br>Secondary: Luana Capel | Mobile App Design |
| | Enclosure 3D Modeling and Development |
| | PCB Fabrication |
| | App Data Management |
| **Electrical Engineering** | **Responsibilities** |
| Jeffrey Sotello<br>Secondary: Kinza Rashid | PCB Design |
| | PCB Fabrication |
| | Power Supply Research and Implementation |
| | Motor Configuration |
| **Computer Engineering** | **Responsibilities** |
| Christian Williams<br>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 (proposed) | Several virtual meetings and 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. |

# Appendix A - References

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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

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 and summarizing purposes.