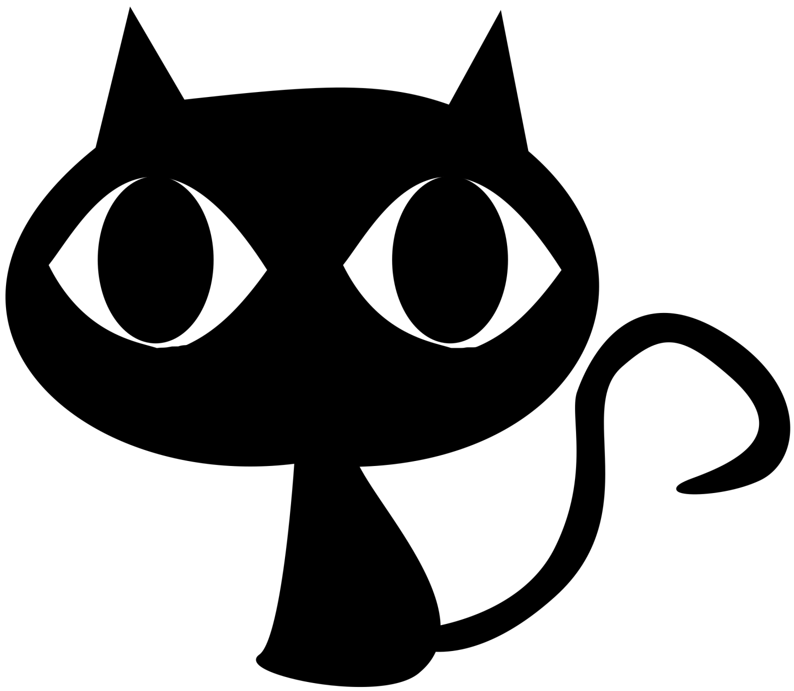
Purrfect Cat Care



Final Project Documentation

Department of Electrical Engineering and Computer Science
University of Central Florida

Group 18

Advised by Dr. Richie and Dr. Chan

Carla Diaz	Computer Engineering	carla.diaz@knights.ucf.edu
David Montoya	Electrical Engineering	gattaca@knights.ucf.edu
Hector Martinez	Electrical Engineering	hmartinez7@knights.ucf.edu
Michael McGarty	Computer Engineering	mcgartym01@knights.ucf.edu
Will Lowther	Computer Engineering	willl@knights.ucf.edu

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1 Executive Summary

The contents of this document highlight the strategies and technical implementation of various components and subsystems in order to realize the key objectives described therein. The description of the system entails monitoring and maintaining the dietary needs of a feline companion and a safe location for defecation. The intent of this system is not to replace the responsibility of the owner to their pet, but to enhance the interaction by notifying the owner of deviations in behavior that would otherwise appear nominal. The scope of this document covers project flow, technological investigation of components and existing technologies, hardware and software investigation as well as component selections to be integrated within the system, different standards used to maintain quality of the product, constraints that impact both the development of the project and its contribution to society, and the design milestones reached in order to realize the final product. Within the subsections, a discussion on aspects regarding compare and contrast of component selection, communication architecture, and programming language selection will inform the reader on the justifications that resulted in specific design choices. Furthermore, a discussion on each level of abstraction clearly defines how the objective is resolved into an automated task.

In opening, a project description of the product will inform the reader a need for this current technology and the overall motivation for why this project was chosen. In support of this need, a project flow of the execution of the design will help illustrate how the project will be tackled and what areas of the design process requires more attention than others. Additionally, a formal declaration of the required specifications will be revealed in order to meet the product's objectives. Finally, coverage of possible stretch goals gives our team additional goals that push the boundaries of our collective knowledge and give the product a more specialized and custom feel.

Following the preliminary segments of the project scope, a technological investigations of available hardware systems, component availabilities, and software implementations are discussed to help refine the selection process and determine what available technologies best support the overall objectives. A variety of different hardware and software components will be integrated within the project, and the best way to make informed decisions is to develop a cross comparison of all relevant technologies.

Coverage of physical aspects of hardware components are investigated and reviewed to determine the feasibility of integrating specific components within each subsystem. There are a number of different objectives that must be met in order to allow for the intended behavior to be executed. Such components like the load cell or the motor may have an undesired response on the system when power or change is introduced, it is incumbent on the success of the project to investigate which components work better together than others. The investigation continues with regards to the software elements of the system. Questions to ask entail which available programming languages are available to easily process the data going from subsystem to subsystem, how will the database be set up in order to respond to data queries and how information will generally be stored, and how will the communication between subsystems be executed. These are all investigation objectives discussed within the software component investigation segments.

There are several Standards to consider as it pertains to design. These conventions allow for seamless implementation of complex subsystems that improves efficiency, provides ease of troubleshooting, yields knowledge of component limitations, and reveal safety considerations for the benefit of designers and the consumer interacting with the product. These standards reveal the notion of secondary limitations that involve socio-economic constraints, environmental considerations, health and safety considerations, and time constraints that dictate what designs are economically and technologically feasible.

Finally, considerations towards system hardware and software design will be discussed in order to describe how each component or software element makes up each subsystem. Each level of system abstraction will be explained in these segments in order to impart details on how the data is processed into meaningful information that the user can understand. Furthermore, prototyping and firmware verification will reveal validation on the implementation of each respective subsystem as a whole product. Once verified, discussion on the product fabrication and administrative content will be covered to reveal the milestones, budget limitations, vendors used, project roles, and general unit cohesion used to allow for the successful implementation of this project.

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2 Project Description

This section describes the motivation, goals, and requirements of the project. It lays out everything from the initial idea to the broad outline of the design. Special attention is payed to requirements, and how trade-offs between desired engineering and customer goals might me made. Constraints will be discussed in detail in chapter 7.

2.1 Background and Motivation

Waking up every morning with small paws walking across the bed or a cold nose to the hand can be very rewarding if you are a pet lover. According to the 2017–18 National Pet Owners Survey approximately 84.6 million homes own a pet. The friendly, playful, loving, and independent qualities of cats make them a fantastic companion. While independent, cats rely on their owners to satisfy the basic needs of food, water, shelter, and welfare. Taking care of an animal can be a demanding job, but pet owners have a responsibility to keep the animals safe and healthy. Maintaining the health of one's cat can be an especially difficult task. Due to their independence, and subtle behaviors, it is often difficult for pet owners to notice the subtleties of their actions. Differences in eating, or water intake typically go unnoticed, and over time may lead to a trip to the vet. Hence, developing a product to track an animal's feeding, hydration, and litterbox habits is the perfect avenue to blend convenience with functionality.

The market today, offers a variety of different automatic dispensing systems for feeding and hydration. Even systems that automatically clean the waste from a litter-box have been a tremendous hit. While these functionalities offer the pet owner the necessary flexibility and automation of mundane responsibilities, these systems do not offer key features that may be important to consumers everywhere, statistics. Most systems now a days offer statistical tracking like number of steps a consumer may have travelled in a single day. There are even applications that monitor calorie intake over the course of a week if the consumer is diligent enough to maintain these records. As technology gains more and more momentum, informational analysis assists the everyday consumer with the power to track and motivate future behaviors. That's why our team felt the implementation of statistical tracking should be incorporated within a pet health care system.

The need for such a system relates to the persistent reports on the number of pet owners that take their pet to the veterinary's office. Several pet owners report that top reasons for not taking their pet to the vet stems from the lack of a need to do so, ranging from logistics of prepping and shuttling their companion weighed against the fact that there appeared to be no visual indication that such a need is necessary [119]. A survey taken in 2011 mentioned in a statistical blog from the American Veterinarian Medical Association, Katie Burns reports that 44% of cat owners do not take their pets to the vet. She confirms in the blog that cat owners choose not to due to a lack of need [19]. Although it may be recommended that annual visits should be considered to ensure a healthy life for the owner's cat, but most owners fail to recognize the signs of a cat in poor health. According to Hunter and Yuill, Doctors of Veterinary Medicine (DVM) in an informational blog, cats have developed the ability to subdue any signs of illness to prevent unexpectedly falling prey to predators in the wild [85]. Although domesticated cats generally do not need to worry about predators in the home, this is an evolutionary trait that serves cats passively. Both DVMs agree that noticing these signs early on allows for speedy recovery and prevention of extreme modes of treatment that could be costly in more ways than one. A few suggestions they offer include sociability, energy levels, appetite, litter-box usage, and overall appearance in terms of coat sheen. Critical signs they suggest include appetite, which they stress that if a cat has not eaten anything in 24 hours, the owner should seek veterinary attention. In a publishing by John Elflein, statistical information provided shows common health conditions in cats and dogs was dental disease in the year of 2017 [93]. These may manifest in the form of social withdrawal as revealed by Dr. Hunter and Dr. Yuill. In each case, reasons for a pet owner to not take their cat to the vet may be traced back to this passive trait.

Based on these observations, the senior design team sought to fill this demand by developing the Purrfect Cat Care system that builds on existing technology based on automation but includes a tracking feature that notifies the user of minute changes in their cat's dietary consumption. This product enables the user to see feeding and hydration trends that may otherwise remain a mystery. There may be a variety of reasons why felines carry out their various needs throughout the day in the order or frequency that they do. The team's goal is to support the pet owner in their relationship with their feline companion by offering feeding and hydration tracking information that notifies the user of the frequency their fuzzy buddy eats and drinks throughout the day. This information may be important to identify underlying issues that manifests over a long period of time. For example, if it is known that the user's cat eats at regular intervals in specific amounts, this data would be recorded for future analysis by the owner. Furthermore, if sharp trends appear (i.e., the cat does not eat for an entire day), the user is notified to focus attention to their furry companion and visit their nearest veterinarian. This service does not end with the cat's feeding and hydration needs, frequency of visits to the litter-box also may indicate changes in feline behavior or quality of health. Should the cat visit the litter-box fewer and fewer times over a course of a week or month, this could indicate a disturbance in the cat's environment that it wishes to avoid, or it may be indicative of deeper intestinal or urinary issues. The bottom line is the fact that the user would be notified of these changes in their cat's behavior to seek professional advice before it is too late.

In its development, it is the hope of the team that this product enables a long-lasting relationship between the owner and their feline friend. In many cases, cats provide the right amount of affection and intrigue that excites pet owners everywhere. As discussed, there are several cases in which a cat's health is neglected due to a lack of signs. It is confirmed that a lack of signs does not necessarily indicate positive health conditions for felines. Furthermore, the current market does not provide such instances in which statistical tracking enables a clear indication of feline well-being. Although it should be noted that the Purrfect Cat Care system does not diagnose health problems for cats, it does notify the owner of anomalous changes to baseline statistics. These statistics could be precursors or underlying ailments that can only be identified by trained professionals. Based on all these considerations, we seek to prolong this relationship by informing the owner of deviations from baseline statistics for them to take the necessary actions. Through the member's combined knowledge accumulated over the course of their individual educational journey, they apply the skills and technical expertise necessary to realize both the objective of creating a desired product and mastery of the fundamental skills accumulated throughout their training.

2.2 Process Flow

In order to design the functionality of the entire system, it was important to understand how each piece of the system interacts with the others. The following describe use cases for each of the systems and how the components will work together to provide service to a frontend user of the Purrfect Cat Care system.

Food Station: The food station when plugged in for the first time will be initialized by connecting to the base station's wireless local area network (WLAN). Once it is connected, it will send a request to the base station to get the daily feeding schedule which will arrive as an array with the scheduled feeding times, up to five total, in hours and the corresponding dispense amounts in grams for each of those scheduled times. If the user has not yet entered a schedule into the system before connecting the food station, it will have a default value of at least one feeding time and the minimum dispense amount. When dispensing, the system will keep track of how much food it has dispensed for that day and if the dispense amount scheduled is more than can fit in the bowl, the system will only dispense up to a maximum amount which can fit in the bowl rated for the system. Because the system will use a load sensor to detect the amount being dispensed, it can sense if the bowl is missing and delay the scheduled dispense. Furthermore, the system can detect if the food container is empty or there is a problem with dispensing the scheduled amount into the bowl, which will prompt an alert to be sent to the user application. In addition to automatically dispensing food into a bowl, the food station will also track how much the cat has eaten per day. The system will send updates periodically to the base station, through its WLAN connection, the cumulative amount the cat has eaten from the bowl. This will allow the user to be as up to date as possible on their cat's feeding habits and will not require any prompts from the user to request the most updated information. The updates will also be able to detect whether the bowl was removed for cleaning while it is reporting in the sensor data and therefore will not report any amounts that do not make sense. During the updates, the system will also be able to recalibrate the load sensor after being cleaned.

Water Station: The water station will be initialized when plugged in for the first time in the same way as the food station. The water station will not require any schedule to work as it will keep the water bowl full at all times and therefore will only require that the reservoir be filled by the user to the max line indicated inside the container on initial setup and when empty thereafter. When dispensing, the water station will always fill the bowl to the max amount to keep the bowl full of water for the cat. The sensor reading will be conducted in much the same way as the food station as well. The only change is that there will be a way to tell if the reservoir is close to being empty using a level sensor, which will send an alert to the base station when the amount is below a certain threshold to prompt the user to refill the reservoir.

Waste Station: As one of the simplest subsystems in the Purrfect Cat Care system, it only reports to the base station when the cat has triggered the proximity sensors whether the cat urinated or defacated by using the humidity sensor. If the humidity sensor detects an increase in humidity after a programmed amount of time after the cat has stepped in the litter box, it will report back to the base station that the cat urinated, otherwise it will report that it was stool. In the same way the food and water stations connect to the base station upon initial startup, the waste station also has the same simple initialization. After being initialized, the waste station will begin to make update requests to the base station with a report of stool or urine when the proximity sensors are triggered and the base station will make the updates to the database with the timestamp of when it gets the request from the waste station.

Now that the process flow has been covered, in order to understand how the systems will work together, the process for communication between systems is mapped out below. The process was mapped out using an Interaction Overview UML Diagram which maps out the interactions between the each of the systems, more specifically, the interaction between each station and the base station. The following figures show the individual interaction overview diagrams for the base station updates, food station updates, and the interactions between the user and the system.

Figure 1 outlines the updates made to the base station from each of the subsystems. Each subsystem will automatically trigger the sensor reading and reporting to the base station contained in the firmware. When the sensor reporting is triggered, each subsystem will send its sensor data via the Wi-Fi module to the base station and the base station will then update the database with the information.

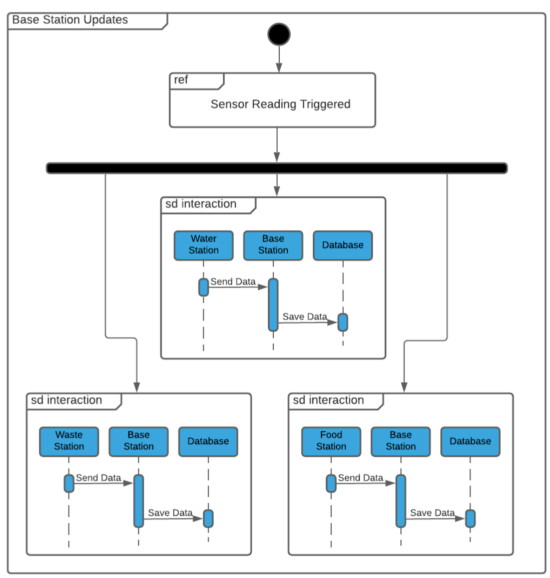

Figure 1: Base Station Updates

Finally, in Figure 2 shows how the user can update the feeding schedule information through the web application and how the information will be updated to the database from the base station. Then feeding station will request the new shcedule each day where it will be stored in the onboard memory of the Wi-Fi module, which will also work as the microcontroller.

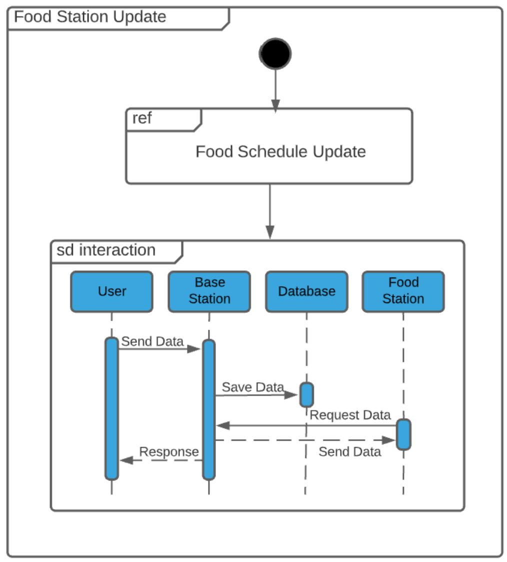

Figure 2: Food Station Updates

2.3 Objectives

The goal of this project is to provide cat owners a convenient and completely automatic way to track their cat's health, while also filling the role of other automatic cat chore systems. The hope is to create a cost-effective, reliable, autonomous, and easy to use monitoring system that handles many of the common chores associated with keeping cats. The system must also be able to detect small changes in the cat's behavior. In order to meet these goals, the Purrfect Cat Care system will consist of four main subsystems: the feeding station, water station, waste station, and base station. The table below formulates how each subsystem will address the project objectives.

The feeding station will handle the food intake of the cat. To be autonomous, it will dispense a user-determined amount of food at regular intervals throughout the day, similar to off-the-shelf cat feeders. However, it will also measure the amount of food the cat eats. Changes in a cat's diet can be indicative of numerous feline diseases, including diabetes, digestive problems, and dental problems. By tracking the weight of food consumed each day by the cat, increases or decreases in appetite can be detected. In order to accommodate the objectives of the system as a whole, the food station utilizes a plain stain-less steel bowl, which is both cost effective and of food-grade quality. The intent is to allow for longer periods where food may be allowed to rest yet mitigate bacteria growth over short periods of time. Bowls made of plastic, or other such materials could receive deep grooves from scratching or food wear. These grooves can

Objective:	Description:
Cost-effective	• Each subsystem will not cost significantly more than current market products. • A litter box will be retrofit with sensors to minimize product cost from mechanical components.
Reliable	• Each subsystem will interact independently of one another.
Autonomous	• A minimum of 7 days of dry food will be held. • A minimum of 7 days of water will be held. • Waste will be cleared automatically minutes after use. • Food and water schedule will be remembered until updated by user.
Ease of Use	• Each subsystem will require minimal intervention: Replenishment of food, water, and litter. • User-defined settings will be done through a website. • Alerts to the user will be provided when food, water, and litter supply is low.

Table 1: Project objectives with description.

encourage the bacteria growth to latch on and persist even after the bowl has been cleaned. Stain-less steel has been proven to be a reliable food-grade material in the cooking industry for decades, and implementation of this selection made it a sensible choice. The food station additionally incorporates a food reservoir which dry food may be stored for at least 7 days. Freshness of the food must prevent exposure to air which will oxidize the food and leave the food stale and undesirable. To this end the food reservoir will include an airtight cap which will make refilling the substation a simple task. The food bowl will rest on a precision scale intended to allow for persistent measurements for extended periods of time. The sensor choice will be discussed in a later section, but the intent is to gather reliable data that does not drift in measurement values due to deformation of the sensor. To this end, the longevity of the product enables a cost-effective solution minimizing part replacement for long term ownership of the product. The sensor provides real-time data to the system controller allowing for autonomous tasks to take place in the absence of the owner. If the scale reaches a value below a certain threshold, the controller would be informed of this change and trigger the event to refill the bowl.

Finally, the food delivery system introduces a 3-D printed part that is made from Polylactic Acid (PLA) which is a non-toxic biodegradable material that costs pennies to the dollar used to print the necessary part. This enables the flexibility and cost effectiveness to design a part that is functionally optimized for this application. The 3-D printed part utilizes a food-auger delivery axle that, when spun about its primary axis, pushes the food from a reservoir between the main food reservoir to the bowl. The use of a quality stepper motor allows for precise rotations of how much food should be dispensed into the food bowl at any given time. The original equipment manufacturer (OEM), which could be found in the bill of materials, of the used stepper motor offers quality development and expert machining at a reasonable price. The likelihood of failure in the short term is unlikely, which ultimately extends the life of the product.

The water station serves a similar role. It will automatically pour the cat's water supply to keep the owner from having to provide fresh water each day. It will also track how much water the cat drinks each day to ensure that the cat is adequately hydrated. Since a lack of hydration can be a symptom of diseases like diabetes or kidney disease, it is important the cat always has access to fresh water. The construction of the water station mirrors the food station in all ways but the delivery system. Since the product to be delivered is a liquid, the use of a water pump enables precise control of how much water should be delivered at any given time. Due to the necessity of the system, it is ill advised to dispense anything other than water. Given this, piping material and pump construction did not receive considerable attention. It does require integration with a predefined system that mirrors the food station to work in a seamless way. It is easier to duplicate systems and alter component choices than to develop an entirely new system all together.

The waste station will consist of an automatic litter box that automatically cleans itself. As the team will be using an existing automatic litter-box, an array of sensors to detect how often the cat uses the litter box and what type of waste it is producing will be added to the system for this project. Changes in litter box habits and waste production can indicate digestive issues, urinary tract infections, and other diseases in cats, so this system aims to detect those as soon as they occur. The cost effectiveness of the waste station will require minimal design features beyond the scope of a typical automatic litter-box. Besides the cost of this type of litter-box, the sensors will cost a small percentage of the entire system. The reliability of the litter-box should be relatively consistent being a market product, however the goal would be to adjust the reliability of the sensors to meet this demand. Once incorporated within this subunit, the sensors will autonomously read whenever the cat enters the litter-box. The objective is to ensure false readings are circumvented using redundant measurements across the station. The system will be able to report these findings to the user with minimal interventions.

All the information collected from each station will be sent to a central base station for recording and processing. The base station will calculate statistics of the cat's behavior, such as mean and standard deviation, and can detect outliers that might indicate health problems. The base station will also present a simple interface to the user that shows their cat's history and current statistics as well as allow the user to control the feeding system. The development of the base station includes minimal expenditures due to the simple design and layout. The remaining considerations of reliability, autonomy, and ease of use will depend heavily on the processing unit used to prepare the information for the user.

2.4 Requirements Specifications

The requirement specifications for this project are broken down by system. There will be slight overlap between various systems, but we have included it this way to emphasize that each subsystem is independent from one another.

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System	Description	Value	Unit
Food:	Minimum Dry Food Storage	1	kg
	Maximum Dry Food Serving Size	90	g
	Minimum Dry Food Serving Size	30	g
	Maximum Dispensing Time	3	Minute
	Maximum Weight Error	10	g
	Operating Power Draw	<20	Watt
	Physical Size of system	30x30x60	cm
	Minimum Pwr Supply Eff.	75	%
Water:	Minimum Water Storage	1.5	L
	Maximum Water Serving Size	60	mL
	Minimum Water Serving Size	10	mL
	Maximum Dispensing Time	3	Minute
	Maximum Volume Error	2	% of M.S.
	Minimum Dispensing Interval	1	Hour
	Minimum Water Level in Reservoir	80	%
	Physical Size of system	30x30x30	cm
	Maximum Operating Power Draw	<20	Watt
Waste:	Operating Power Draw	<20	Watt
	Maximum Detection Distance	1	m
Base:	Operating Power Draw	<5	Watt
	Data History	12	Month
	Communication Delay	<5	Second
	Physical Size of system	30x30x30	cm

Table 2: Requirement specifications list.

Food Station

The food station is a modular subsystem that must meet specific requirements in order to realize the overall objectives. For a system of this type, the food station should maintain a maximum storage of at least 1kg. This allocates the necessary sustenance to be dispensed throughout the week in the prescribed portions, daily. The feeding event will be limited to a frequency set by the user. This offers the flexibility for the user to adjust the diet and habits of their cat prescribed by their veterinarian. The maximum dry food serving size should not exceed 90 grams, since this could potentially skew the results due to possible spillage if the bowl were full. This upper limit represents the total amount of food that a cat might eat within the span of a day. A minimum dry food serving size of 30 grams may also be set in order to provide fresh food throughout the day as the cat eats. This range allows the user to be able to either dispense the full daily recommended serving to their cat or allow for more control to regulate the routine of their cat's feedings. This minimum dispense amount also take into account the accuracy of the weight sensor at measurements requiring higher sensitivity.

The manner in which the delivery system must provide food will be limited to 3 minutes for any given dispensing event. The intent is to ensure that the delivery of the food is provided in a reasonable amount of time, while also providing a range in which the speed of the dispensing event may be controlled. Additionally, this allows for flexibility in the design of the delivery system, in the event one design is more efficient and successful than previous iterations. In addition to the amount of time it takes to dispense the food, redundant measurements from a sensor should reflect a tolerable maximum weight error of 10 g. This allows for some level of guarantee that the amount of food the cat has eaten is accurate and not absorbed due to creep error.

In order to execute these tasks, the operating power draw allocated by this module should not exceed 20 Watts. Although it is not likely to reach 20 Watts of power, this should be enough to power the motor that drives the delivery system, which, in turn, is run by the various electronics and communication devices within the system. Given this, it should operate with an efficiency of at least 75% in order to not damage sensitive circuitry. In its entirety, the system offers flexibility in subsystem redesign in the event additional features can aid in system performance and accuracy.

Finally, the dimensions of the subsystem's footprint should not exceed 30x30x60 centimeters per length, width, and height. This offers robustness in design which would be able to accommodate additional mass of food storage and the mass of the motor and electronics that run it while not being bulky. These dimensions fall relatively consistent with the other modules and is small enough to be highly portable and streamlined.

Water Station

One of the project's primary goals is to have enough water in the water station reservoir to last at least seven days. Experts advise individuals not to take vacations longer than a week to avoid stress from accumulated workload. It also wouldn't be reasonable to leave pets alone for more than a week anyways. Therefore, giving the user the ability to go on vacation for up to a week without worrying about their pets' health is a feature that no other product offers in the current market. Since a cat generally drinks 120 mL on average of water per day, this came out to a minimum of 1.5 liters of water in one week. This determined the minimum amount needed to be held in the reservoir. The minimum and maximum serving sizes are determined by the sensitivity of both the load cell and water flow sensor. For convenience, the maximum dispensing time was set to 3 minutes as the water dispensing time should be completed in time for the cat to consume at a regular schedule.

Waste Station

The retrofitting of a litter box naturally limits the complexity of requirement specifications since the system is relatively simple. The focus of these specifications will involve the system's power requirements and the total number of uses. A power requirement of 1 Watt will be more than achievable for the few components being driven. A system controller, proximity sensor, and counter are very unlikely to require more than one Watt of power based on previous research. However, the one-Watt limit is in place to allow some freedom regarding proximity sensor choice.

The only other significant requirement stems from the chosen litterbox. For the design of the litterbox, it was decided that the system should be calibrated to be fitted onto an array of different systems. It was reasonable to conclude that, should a desired system include a waste station that is larger in size to accommodate different sized species of felines, a minimum detectable distance the sensors should achieve is 1 meter. Most litterboxes are smaller in size, however this inclusion should cover these edge cases.

Base Station

The base station is the most hardware integrated system. Development boards such as the Raspberry Pi, Jetson Nano, and Arduino based systems are very conservative in their power requirements. Therefore, a typical operating power of less than 5 Watts is more than achievable. The only moment the power draw would potentially increase is during a wireless communication. A brief search of wireless packet duration is on the order of microseconds. Each of the three modules, food, water, and waste will be communicating with the base station. In the worst-case scenario of all three stations queued for a communication it is likely that the communication may complete in a span of 5 seconds. Similarly, when the user requests the state of the three stations a 5 second duration is not uncomfortably long for a user to wait. However, it is expected that the communication delay will be much less than 5 seconds.

The physical size of the system is given to be 30 cm in each direction. This value is a standard size that any of the three subsystems could fit within. The station size may seem large for an embedded system, which typically has dimensions on the order of a few centimeters in each direction. However, the large physical dimension allows design freedom in attaching the base station directly to any of the three other stations and airflow. If the base station were permanently attached to the water station, then a 100 cm^3 volume would not be enough to encompass the total size.

The final requirement is the systems data history. Data history is defined as the maximum length of time data will be saved for. A 12-month history will allow the user the ability to track certain periods of their pet's behavior. Some pets may have a preference of eating more in the winter as opposed to summer and some common ailments are periodic in nature, such as allergies. The long data history would help pet owners and veterinarians to determine if a particular ailment is a one-time occurrence, seasonal occurrence, or if something more urgent may be present. Approximating the expected size of a data entry to be a kilobyte per day, it is incredibly unlikely for the on-board memory to reach full utilization.

2.5 House of Quality

In the pursuit of developing a product that is both useful and marketable, the designers of any system must consider key areas that often counteract the efforts of improvement, such as enhancement in one area and performance degradation in another. Based on the details outlined in Chapter 3 Requirements Specifications, the subsection on Advance Requirements Analysis explore methods to develop requirement specifications and the respective tradeoffs should one realization take precedence over corresponding marketing requirements. The usefulness of these comparisons may be organized into tables that generate strong or weak correlation between two distinct types of requirements, market appeal and engineering objectives. In this segment, a brief description of the requirements necessary to realize the overall objectives are compared in a three-table matrix called the House of Quality (HoQ). This table compares correlations between specific requirements with marketing requirements that make the product potentially appealing to the consumer. The HoQ is a combination of an engineering trade-off matrix, a competitive benchmark, and engineering-marketing tradeoff matrix. Through the use of these matrices, polarity and correlation aid in the transparency of how features and requirements may influence a design to take a route that is realistic as opposed to overly ambitious, unmarketable, and complicated in design. It is mentioned in the text that engineering requirements should be abstract, verifiable, useful, and unambiguous. Once developed, they should be then normalized to minimize redundancy, represent the complete needs of the project, and they should be bounded. The HoQ presented in Figure 4, has been adapted to focus on what is believed to be the key factors influencing this project.

In column 1, convenience has a strong positive relationship with capacity. This grants the consumer the option to allow the product to be self-maintained for long periods of time if need be. This also offers a strong relationship with autonomy as well as a moderate correlation with cost. These features grant the investors the opportunity to see what correlations are more beneficial than others. The subsequent columns follow a similar trend based on the arrow indications. The top of the diagram, compares the correlation between each engineering requirement and how they support or impede each other. For accuracy and memory capacity they share positive correlations with user interface. For the case of memory capacity and user interface, there is a positive correlation, which indicates that as the size of the memory increases, the variety of information available to the user also increases. Additionally, a positive correlation is shared between accuracy and the user interface such that as reliable data is recorded consistently, the more trustworthy and useful this data may be to the user if translated into digestible information. As previously mentioned, Figure 4 informs the reader on the relationships of engineering requirements and their influence on marketability. The section at the bottom of the HoQ iden-

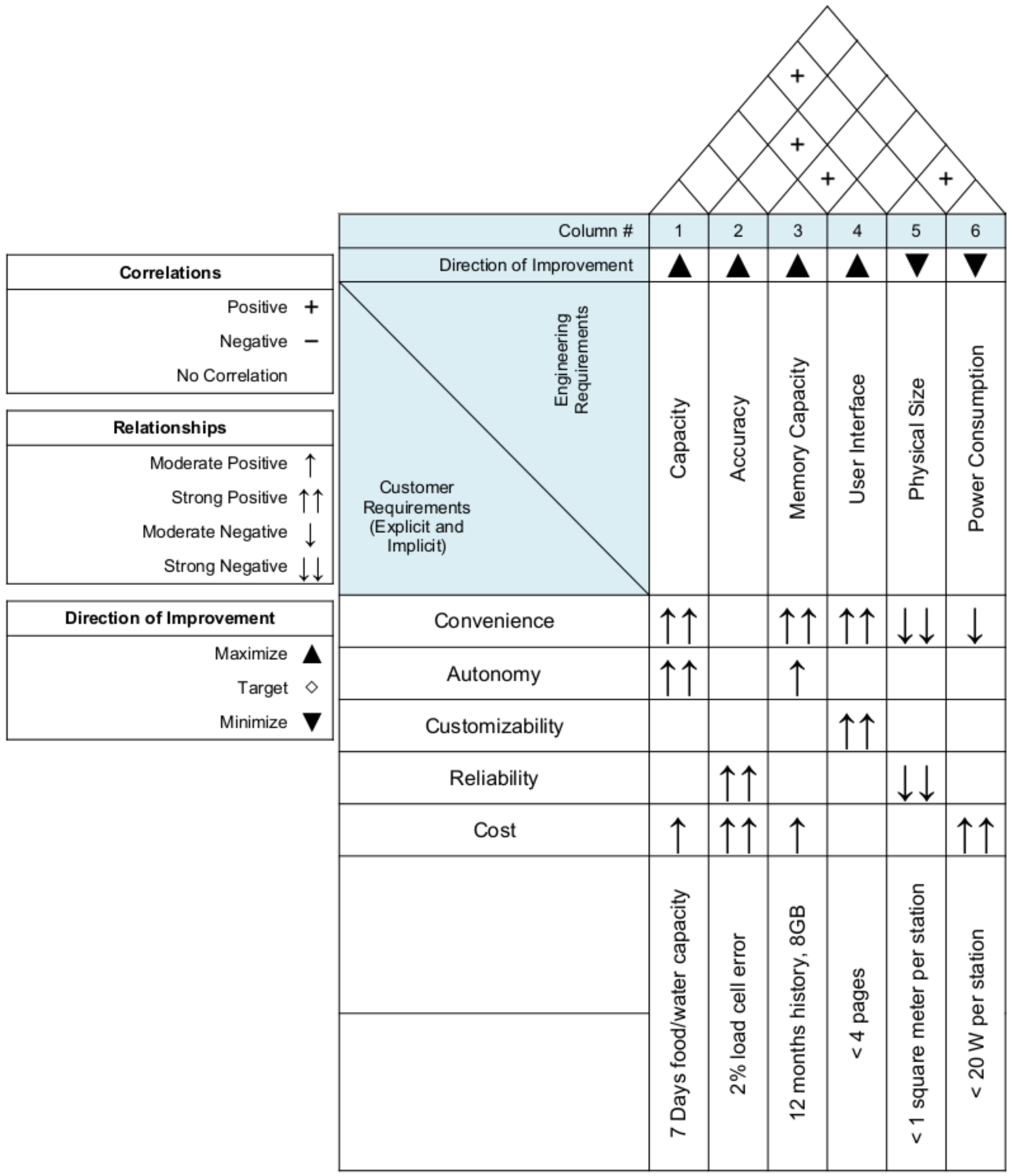

Figure 3: House of quality diagram

tifies a bit more detail as it relates to each column. This is used to clearly state the intent of each column and potentially outline its impact with the marketability of the product as a whole. Through the combination of the three matrices, there is a distinction of which requirements have a bigger impact on the appeal of the system versus its usefulness.

2.6 Stretch Goals

Due to the complexity and scope of the project, only a select number of features may be incorporated due to the time constraints. The objective is to get a working prototype implemented and work out any features that do not flow or interact with the rest of the system as intended. There may be additional features that enable the existing design to work more efficiently or provide additional functionality. This segment covers possible stretch goals that could be achieved, time permitting, in order to improve upon the existing design or incorporate an element of customization. One possible feature involves the portability of the respective stations which would allow for better positioning if a wall connection were not available. A second possibility involves the implementation of a Radio Frequency (RF) tracking system that may be attached to the cat's collar, which interfaces with the various modules to provide an element of redundancy to the system to ensure false positives are not occurring. In the same way RF would be used as a redundant measure, the team considered adding a camera incorporating image processing to determine if the cat was at a particular station. A fourth feature includes a pause button that allows for the temporary suspension of the measurements provided by the subsystems in order to save energy and prevent corrupted data from being recorded by the base station. This would be useful for when the user would like to disable the system temporarily because they are either going to be out of town and do not require its operation, or they want to clean an element of the system and do not want bad data being sent accidentally, among other reasons to they may want to disable the system temporarily.

The first stretch goal revisits the notion of how the subsystems will be powered. As it stands, the intended approach involves each system to use line power. To redefine how the system will receive its power would take a bit more time and research in order to accommodate the power requirements of each respective modules. Additionally, it would involve a better understanding of how power is dissipated throughout a particular module and determine an optimal way to utilize the energy from a battery source, since the objective would be to maximize the life modules in order to limit battery replacement. The more frequently the batteries are replaced, the less affordable the system becomes in the long run.

The next stretch goal involves the development of a Radio Frequency (RF) sensor that could be integrated into the system that provides additional redundancy and improved accuracy of the data. Possible benefits of developing this technology includes ways to inform the owner of where the cat tends to spend most of their time when the owner is away. This could confirm possible sickness or a change in the cat's environment that would not be immediately apparent to the owner. The development of a custom RF sensor would mainly test the team's ability to expand on current knowledge in product design to a more focused area of antenna design. This is a more specialized field, and most of the team hopes to explore this feature.

The stretch goal of adding a camera and image processing was albeit a larger stretch goal as it would require additional hardware components and more involved software development, but it was something the team thought could benefit the project. The image processing could be used in the same way the RF would be used as an additional redundancy of data collection verification. It could also be used to incorporate additional features, such as tracking certain cat behaviors like activity level to detect lethargy or healthy excitement levels. Although it seems like it would be quite the undertaking to add this feature, the hardware component can be purchased and the only added work would be in the way of processing the images captured by the camera via software.

Finally, implementation of a pause button into the base station would enable a more stable and uncorrupted data to be processed. When the owner decides to clean the bowls of each module, the sensors potentially will still be powered on. Current design approaches may involve logic rules to dictate how to determine if the bowls have been removed and be placed on a low power mode setting. There may be a need for the user to indefinitely turn off the sensors while cleaning the bowls. This feature provides a redundant manual override that the user may take advantage of given the circumstances.

The inclusion of these features would enable a possible means for improving efficiency of the system and added functionality. These features do not prevent the system from being realized but enable the team to focus specialized attention to these areas in an effort to stimulate a better understanding for these respective technologies. For the case of the RF sensor, the team would hope to gain unique insight on how antennas work and best practicing methods to capture the appropriate signals from a distant transmitter. In the same way, the image processing involved in the camera implementation would provide experience in a growing field of image processing, a precursor to machine learning. Mobile power for the subsystems would enable the user to place the feeding, water, and waste stations in any possible location to either optimize the transmission time between modules or out of pure preference of the cat. The feature of providing manual control of when the sensors take measurements can be beneficial in a number of different ways, allowing the user to have a broader spectrum of control. While it would be desirable to implement all the mentioned stretch goals within the project scope, time does not always permit these goals to be met. These are optional objectives that the group decided the project could benefit from but does not require in order to function properly and realize their goals.

In the months concluding the final semester of the project, most of the stretch goals were not met. The power revision maintained such a low power draw anyway, as high as 80% efficient at least on all four subsystems, the need for redesign was not considered. The idea of battery waste has an impact on the environment also contributed to the decision of omitting this stretch goal. The use of RF sensors and Camera/Image processing were not able to be integrated either due to the lack of research on this front. The implementation of Image processing to recognize features of a cat would require extensive samples of data and hours of training on top of the development of a nueral network that may make these definite distinctions. The RF sensors, as independant design opportunity would require knowledge of antenna design and intimate understanding of microwave engineering, that none of the team members possess. If these were to be a feasible objective, research would have to have been done by the end of SD1 and parts bought during the break. Due to hang ups on other fronts regarding the development of the circuit design and component characterization, these had to remain on as a tertiary priority.

Finally, the development of a pause button, was omitted due to the added complexity the system would have to consider. Having a button would mean that the user would have to think about performing this action rather than simply removing and cleaning the bowl at their leisure. The implementation of firmware supported the purpose a simple button offered.

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3 Technological Investigation

In order to design a functional product, investigation was done into both current existing technologies, and the technologies required to create the project. The current market contains solutions which are similar to the Purrfect Cat Care system, but our solution expands on current technology due to the additional data collection. Throughout development, it was necessary to determine what technologies will be required to build each component, and how to select parts and materials to meet the requirements specifications. Attention was given payed to both hardware and software components.

3.1 Current Market

The current market of cat care automation favors cost and convenience above all else. For most people, both cost and convenience are the only concerns. This emphasis on cost has led to the overwhelming supply of automatic pet feeders, water bowls, and litter boxes in the range of $30 to $300 to flood the market. The seemingly drastic price range is due to a varying array of features, some of which will be discussed in the following sections. Many devices offer week-long food and water storage, and up to 50 litter box cleanings. These capabilities offer a convenient experience to the owner, however, they lack significant innovation across the market. Our project aims to provide additional value to justify a larger price point through the recreation of the product with data collection capabilities. Tracking quantities such as food and water intake, as well as litter usage provides a breadth of information for owners and veterinarians. It is the team's hope that the additional of data collection capabilities becomes practice to potentially save the lives of cats whose ailment may have been caught too late otherwise.

3.1.1 Feeding Stations

The current market of automatic dry pet feeders lacks significant innovation apart from the physical housing. For cats, a distinction is made between wet and dry feeders. Automatic wet food feeders do exist, although uncommon. It is believed that most pet owners would prefer dry food as opposed to wet food for automation. Most wet food manufacturers place the food inside a closed, single-serving, container. To automate wet food dispensing without extensive mechanics would require the pet owner to empty several of these wet food containers each time the feeder is refilled. Not only does the additional user interaction distract from the autonomous nature of the project it also brings up several sanitary concerns. Dry food exhibits a much longer shelf life then opened wet food. Implying it will be more difficult to ensure the wet food is safe for consumption. Therefore, the scope of this project will focus on dry food within the feeding station.

Provided in the figure is a standard automatic food bowl. The figure is provided courtesy of

Closer Pets and is the CatMate C3000®. The feeder may be broken into four main components: food storage, food bowl, embedded electronics, and the mechanical dispenser. Some products may have a physical user interface for the user to adjust timing intervals and quantity, whereas other products may use a mobile app or website to remotely adjust these settings.

Figure 4: CatMate C3000®automated feeder [14]

The food bowl and reservoir are relatively fixed from a design perspective. The bulk of the system's design lies in the mechanism dispensing the food into the bowl and the complexity of the feedback network controlling the dispenser. The intention of this project is not to design complex mechanical systems from scratch, so in favor of simplicity the design will be focused on a system controller, such as a microcontroller, and how the system interacts with the user.

While ignoring the mechanics would be convenient, several components will need to be purchased. Depending on brand of automated feeder, the dispensing mechanisms will vary. Some common dispenser types are step-controlled hinges, power screws, and wedge rotors. See Sec. 4.8 for a thorough design discussion of these mechanisms. The choice of mechanism will directly control the accuracy of food to be dispensed. If the accuracy may be tuned with a mechanical design it is another avenue to alleviate burden from the system controller. These descriptions of the automatic feeder may seem redundant, however, the inaccuracies of the system will need to be dealt with. Designing an automatic feeder costing on the order of hundreds of dollars would likely not be a popular product. Hence, the inaccuracies of each mechanical part will need to be addressed and characterized in order to minimize the error of the system, and to reduce the complexity of the controller firmware.

3.1.2 Water Stations

Technological investigation has revealed that automatic water feeders fall into two drastically different families: gravity bowls and fountains. Both types of bowls do not accurately regulate or track the quantity of water within the bowl. Cats are excellent at regulating their water intake and drink only when necessary, due to their desert-origin. The water content from wet food also adds to their daily intake, making it difficult to accurately track how much liquid a cat consumes throughout the day. Regardless, the inclusion of water tracking will prove helpful in characterizing the long-term behavior of the cat. In essence, the quantity of water does not matter the variation across weeks and even months matters.

Gravity Bowl:

Figure 5: PetMate Replendish Feeder with Microban®. [124]

The gravity part of gravity bowls hint at the use of gravitational force to dispense water into a bowl. A gravity bowl consists of three core components: a water reservoir, a water bowl, and a floating plastic disk. The disk is attached to the reservoir and regulates the flow of water to the bowl. The flow rate is determined by the volume currently in the bowl. If the bowl is full the disk experiences a buoyant force that pushes the disk away from the dispensing vent. While the disk experiences this buoyant force the disk will not touch the bottom of the reservoir, blocking the flow of water. The only moment when the flow is blocked occurs when the reservoir is empty.

A gravity bowl is an incredibly convenient and simple solution. The primary downside, with respect to this project, is the lack of filtering. One team member owns a gravity bowl and has to clean the bowl several times a week. Cleaning the bowl 2-3 times a week is likely overkill. However, a cat will likely to go to the water bowl immediately after eating. Ingesting a full serving of dry food is is likely to leave the cat thirsty and and crumbs in the cats mouth or on their face will fall into the bowl. There is also the concern of an open bowl contaminating the reservoir is something potentially harmful falls into the bowl. The above criticisms were considered throughout the water station's design.

Fountains:

Figure 6: PetMate Fresh Flow®water fountain. [123]

Water fountains take a significantly different approach from gravity bowls, opting for constant circulation of water within the system. A dedicated filter is present to keep the water clean and in motion. Several sources, including a team member, confirm that some cats prefer their water to not be stagnant. If the water has been sitting for too long, the member's cat will physically move the bowl or slap the water with their paw. It is unsure why cats behave like this, but it provides an interesting edge case to consider throughout the design.

An example fountain is provided by PetMate Fresh and shows the Flow II®water fountain. The Fresh Flow combines the reservoir and fountain into a single entity. The bulk of water sits inside of the bowl and the tiny vents allow water to be pumped through, filtered, and dispensed through the top of the pump. Various other products include a dedicated reservoir of unfiltered water. As the volume in the bowl decreases, unfiltered water is added into the system for filtering and a fixed volume is maintained.

A significant downside of this design is the heavy reliance on a pump. It is likely that the pump is on continuously or pulsed every few minutes. Consistently running the pump places the failure point on the pump. Regardless of the maintainability of the product, the mechanical parts should be run as conservatively as possible. The use a pump is inevitable in the project's design. However, an emphasis will be placed on maximizing the lifetime of mechanical components.

3.1.3 Waste Stations

The autonomous nature of our project has restricted our scope to automatic litter boxes. The waste station is the most mechanically involved of the subsystems. This project will not recreate the mechanical automation. Hence, a choice was required in determining which litter box will be used in the final design. Refer to component selection for the litter box decision. The automated litter box market is divided into two categories: Rotating Platform or Comb Movement. This discussion is necessary to determine which devices will be most easily retrofit for the data collection modules.

Comb Movement:

The simplest of the two types, comb litter boxes have a motor which drives a comb-shaped piece of metal through the litter box. These systems typically use a propriety high-absorption litter, which absorbs nearby moisture to dehydrate cat urine and excrement. The high-absorption litter quickly absorbs cat urine within minutes of the cat leaving the litter box. A proximity sensor is attached midway through the box to detect if the cat is within the box. Once the cat leaves, a user-defined timer counts down before activating the motor. A timer is necessary as to not scare the cat, giving it adequate time to leave the immediate vicinity. Once the motor is activated, the arm combs through the litter and the excrement either sticks to the bare metal or is pushed along the length of the box and the small litter crystals pass through the teeth of the comb. At the end of the litter box is a small storage area which holds the dried excrement. Over time the excrement will dehydrate and detach from the metal comb.

Figure 7: PetSafe Ultra Self-Cleaning®Litter Box. [132]

The relatively detailed explanation above was obtained from a group member who owns an automated litter box. A brief search of automatic litter boxes will result in several products by PetSafe®and Premier Pet®. An example of these types of litter boxes is provided below, with permissions of PetSafe®.

The litter box sits on top of a disposable container holding the litter. Hence, replacing the litter is as simple as picking up the housing, tossing the litter in the trash, and placing a new box underneath it. The front of the figure includes a dark grey slope. Underneath this sloped section is where the dried excrement and any other foreign objects are pushed leaving a clean area for the cat to cleanly it's business. The last feature worth mentioning is a digital counter on the top right of the device. This counter tracks the number of times the motor has activated, corresponding to the number of times the cat has used the litter box. This feature is essential to let the user know when it is time to replace the litter.

Rotating Platforms:

Figure 8: CatGenie A.I.®sifting mechanism. [22]

The rotating platform takes an inverse approach to comb movement by rotating the entire litter box instead of one mechanical piece. The litter boxes are typically round and fixed on top of a rotating platform. The platform allows the litter to rotate and be filtered through a slotted, spatula-like, actuator. The slotted material may be actuated to allow the filtered waste to drop into either a trash can for manual removal, or by a plumbing system. Products by Litter-Robot® opt for a trash can design whereas PetGenie® directly attach onto the owner's home plumbing system for removal. Regardless of the waste destination, the underlying mechanics are the same.

Figure 9: CatGenie A.I.® complete installation.

The market for rotating litter boxes is much less than that of comb litter boxes. A brief search resulted in prices on the order of $400-$500 for these products whereas the comb-based boxes are on the order of $80-$200. The drastic increase in price is likely due to the increased mechanical complexity associated with rotating an entire litter box and ensuring the litter does not clog critical mechanical components.

Provided by PetGenie® are figures of their PetGenie A.I® product. It is beyond the scale of this document to discuss how the rotation of the platform is implemented. Throughout investigation it was deemed unlikely to support this type of litter box. The types of vibration produces by rotating litter boxes would increase the mechanical engineering component of the project. Regardless, the filtration mechanism is present in the figure above. The letters spelling out solids represent excrement which has been captured by the scoop. While the platform is rotating the scoop moves vertically passing through the litter and capturing excrement. Once the scoop reaches its maximum height, the angle is such that the excrement slides into a hopper for disposal.

The initial takeaway was that attaching circuity directly to the box's circuitry is not an option. While this project is not for financial gain, making a slight modification to an existing product and branding it a new product produces several issues. The rotational behavior would likely prevent sensors to be attached directly to the housing. Over time the mechanical motion would reduce an adhesives effectiveness over time. The mounting mechanism needs to be as non-invasive as possible. See Sec. 12.4 for additional information on how mounting to the box was done.

3.2 Hardware

The following sections will present key factors driving component choice for key hardware components. Key hardware components are defined as components such as sensors and driver which could not be easily replaced. Passive components will not be discussed until the hardware design section.The factors discussed in these sections will guide the choice in the following chapter, Hardware Component Selection.

3.2.1 Load Cell

One of the most important sensors used throughout the Purrfect Cat Care system is a force transducer. This seemingly simply piece of hardware measures an applied physical quantity at a point of contact and converts this to meaningful data for a user to analyze. Force transducers can measure mechanical force in a variety of ways, namely: compression, tension, torsion, shear, and bending. In this section, a discussion on how to measure the food and water consumption using force transducers will be explored. A key argument to consider entails which mechanical force measurements will act as a medium to grant insight into project objectives and which type of force transducer may be reliably used to measure incremental changes in mass with minimal error.

The measurement of the cat's food and water intake is a key objective into detecting precursors of health abnormalities. In order to realize these objectives, the device must meet a few key requirements: 1. must measure on a scale of hundreds of grams, 2. must accurately measure small changes to the load, 3. must maintain minimal drift in load accuracy due to prolonged sensor deformation, and 4. must operate on the order that coincides with the power requirements of the specific module and the input into the Analog/Digital Converter.

There are two popular types of force transducers, strain gauges and load cells [8, 154]. The strain gauge is simply a force transducer that is the common throughout the force transducer market. The implementation of this technology consists of a conducting foil distributed in a serpentine pattern upon a nonconducting substrate. Within the physics of resistor technology, the impedance of a signal transferred through a resistive segment may be modeled by R = $\frac{\rho L}{A}$ (Ω). The strain gauge arrangement enables a variation in voltage that changes with the change in area. This means, for a given deformation, in which the strain gauge is secured on the surface of a flexible beam positioned on a ledge, the surface area of the strain gauge increases or decreases. The altered resistance result in a variation in voltage across the element. This useful technique enables other applications of strain gauges, which reveals a second type of force transducer, load cells.

Load cells require an array of force transducers in order to measure how the larger component deforms [125]. This is useful in order to determine the magnitude of force applied at a specific point. When it comes to consumer and commercial use, measurements based on the mass of a product are often used based on the principle, F = m·a. A load cell in this sense, allowing for the Purrfect Cat care system to determine the remaining mass of food or water after every interaction with the cat.

The Purrfect Cat Care system requires this change in food and water intake over a long period of time. In order to meet this objective, the project design required an objective comparison of the available technologies that operate on the order of grams, millivolts, low error per unit of time, etc. Given the functionality of a load cell, there are a number of sub-types to consider when attempting to meet these objectives. The most popular technologies come in the form of hydraulic, pneumatic, capacitive, strain gauge, and piezoelectric. A brief introduction of each sub-type will be explored followed by an explanation for the given selection based on each capabilities.

The use of hydraulic and pneumatic variants often span into mechanical engineering, mobile machinery, lifting gear, geo-technology, process engineering, power generation, and agricultural engineering. They generally apply the same physics, which incorporates fluid dynamics in order to develop readouts that measure force, however most sensors use mechanical means to report data through the use of spring gauges , diaphragm measurements , and valves. Although there exists technology for measurements within the realm of project goals, the tech is still relatively specialized and common sensors measure within the scope of a few kilo-newtons of force [73, 157, 52].

Load cells that take on the characteristics of a capacitor with variable plate distances allow for an alternative avenue for load measurements. Current implementations might incorporate one plate of the capacitor being fixed, while another plate is connected to a load baring tray or beam. When a load is applied, this would decrease the distance between both plates resulting in higher capacitance. This change in capacitance would ultimately vary the voltage output. Based on a number of distributors, like Loadstar Sensors, Automated Process Equipment Corp., SMD Sensors, and Newark Electronics, capacitive load cells are extremely over-priced for project budget, they aren't accurate over long durations, and operate in the range of 10lbs or more.

Piezoelectric devices operate much in the same fashion as a traditional strain gauge load cells. The difference is the implementation of a crystal oscillator that outputs a voltage under compression. An important point to consider in the implementation of these sensors is how it measures applied force. When a static force is applied, electric charge is generated across the crystal. However, due to the fact that the materials used are not perfect insulators, charge tends to leak at the terminals and recombine. The leakage charge indicates that this type of sensor is sufficient for dynamic measurements performed over a brief periods since the measurements tend to introduce error due to recombination [49].

Strain Gauges load cells are a sub-type of load cells that operate as an array of strain gauge sensors arranged in a Wheatstone bridge configuration. The bridge structure results in a differential output voltage that is sensed across the bridge nodes [113]. The most common strain gauge load cells exhibit two strain gauges under tension and two under compression. The pair of four gauges compose the bridge and other variations exist to measure different forces. Regardless of orientation, when in either of these two states, the resistance changes, and thus changes the voltage across them. If the sensors are configured on the surface of a small beam, used to support the sensor and prevent permanent deformation, the end of the beam may measure the applied force at the center of the beam where the tension or compression occurs. The main advantage of this category of sensors, is the streamline implementation of the sensors, the support of the metal beam, and ability to maintain prolonged measurements of static force. This category of sensors are popular amongst high precision kitchen scales and chemistry equipment.

When it comes to a side by side comparison of the previously mentioned load cell sub-types, only one of them meet the criteria for accommodating the prescribed objectives of the project. Strain gauge load cells are adequate for the reasons already mentioned and all that remains is how the sensor will operate in order to track changes in mass. Additional considerations include how the specifications of potential load cells are broken down in order to render the expected output. Typical specifications may include but not limited to, Load cell capacity, Full Scale output, Rated output, and Combined Error. These are a few of the specifications that determine the final decision on which specific strain gauge load cell to select. When it comes to the actual strip that makes up the strain gauge, it was mentioned that the strain gauge is essentially a variable resistor that changes as the surface area changes upon a nonconducting substrate. This is a foil that contains the metal tracing of a wire that alternates in direction in a serpentine patter from one soldered tab to another. These tabs are what connect to the next adjacent component.

When a network of gauges are connected in a Wheatstone bridge and attached to a hollow beam, a pair of gauges are applied to the exposed surface above and below the beam. When a force is applied to the surface of the beam the two gauges on the surface experience tension and the two internal gauges experience compression. Additionally, the orientation of the sensor determines resistance spread of the max and min values. If the sensor is orientated orthogonal to the axis of incident, there will be a greater variance in resistance as opposed to the sensor being parallel. It is important to note that the load cell is not being designed in this project. However, understanding the physics was necessary to best choose components to maximize the output voltage over a given weight range.

Through the use of an excitation voltage, the circuit is provided with the necessary bias to the bridge and the output is measured across the bridge nodes. An adequate range for the systems excitation voltage, must fall in the range of approximately 10(VDC). Since the circuit is in a Wheatstone configuration, two branches of the circuit creates a voltage divider that is the output. This in turn adequately shows the change in voltage potential across one end of the output with respect to the other. This variation implies, that under a certain deformation value, an imbalance of the voltage potential will be present. When no force is applied, there is no deformation and by extension no variance in voltage potential and so the output will be zero.

When it comes to searching for the most suited load sensor for the correct application, there are a few terms that are identified within a typical load sensor data sheet. The first type is the capacity, which is the difference between the highest and lowest measurement the load cell can make. In terms of project objectives, the max dispensed cat food is 100 (g). F_a is a constant that describes how dynamic a system is in terms of Full Scale (%FS) output indicates the percentage of the magnitude of the output voltage when the load equals capacity. This means, when the load cell is at capacity, the output voltage would be 100%. This is important because the %FS output depends on the magnitude of the excitation voltage, which is the input voltage coming from a power source. Data sheets provide information regarding the resolution of the measurements per unit of the input voltage. This is generally regarded as the Rated Output and are read in units of millivolts per input voltage (mV/V). Finally, the Combined Error may encompass a number of different considerations, like non-linearity, hysteresis, and creep error. This may be represented as individual fields, but for this project the measurements must be as precise as possible and must not change over long periods of time as a result of static loads.

One of the key considerations that is common to both systems of the food and water dispensers, is the life span of the sensor. It although it may be convenient to a shear-beam due to its high precision, this type of sensor form factor reveals that it has a relatively short life span. In terms of life span this could be considered as total time a load may be applied before failure. Additional considerations may include a button form factor, in which a flat button exists in order to measure a load. The inconvenience involved in this approach might include a scenario where the load is off centered which results in lower force at the point of incident. These considerations leads to the conclusion that the application of force should be consistently read regardless of position, for this a Single Point form factor may be the most reliable type for this system.

The implementation of force transducers within both, the water and food dispensers have been covered at length within the scope of this discussion. Important factors considered were types of force transducers, the most promising were piezoelectric and strain gauge load cells. After careful consideration, comparisons of both technologies revealed that strain gauge load cells offer consistent measurement readouts over a long duration, which is a main functionality of both modules. Additionally, the capacity of interest had to be on the scale of 0.1 to 1 (kg). The load sensor must operate ideally linearly in the range of 100 (g) since this value is the maximum amount dispensed at the beginning of the day. Given this, the sensor must be sensitive enough to resolve the minute change in remaining mass as the cat decides to eat throughout the day. The load cell, chosen ultimately falls to a single point strain gauge load cell, as it operates within the scale of several hundred grams to a kilogram, produce data with minimal error over time, and operates within the prescribed range for the rest of the independent modules.

3.2.2 Load Cell Amplifier

This section discusses why a load cell amplifier is necessary to condition and digitize the load cell's μV differential output voltage. Partially a misnomer, a load cell amplifier is a combination of differential amplifier with analog to digital converter. To process any meaningful information from the load cell, the common-mode component must be removed, and the differential signal must be amplified. For example, the greatest differential output of a load cell with a 1 mV/V rated output under a 5 volts excitation voltage is 5 mV. This 5 mV range is ideally linear over the rated weight of the cell. A 5 kg load cell under a 5 V excitation results in a 1 µV/g resolution. As a result, lower excitation voltage reduces the resolution further.

In dB notation, 4 μV with a reference of 1 V is equivalent to a -104 dB signal. The dB value is given to reiterate that digitizing with 4 μV steps adds an unnecessary restriction to the system. Hence, a differential amplifier with gain of 128 would increase the full-scale differential output to approximately 2.5 V. A 2.5 V full-scale differential output over a 5 kg load cell gives a quantization of 0.5 mV per gram: a much more reasonable step. Choosing a differential amplifier with a larger gain adds more freedom when choosing a reference voltage for the ADC. The common-mode is ultimately dependent on the excitation voltage used. The Wheatstone bridge model of the load cell produces a common-mode component half that of the excitation voltage. For large excitation voltages the common-mode rejection ratio of the amplifier must be larger to minimize the DC component seen by the amplifier. As given above if an amplifier with a common-mode rejection on the order of -100 dB would reduce the common-mode component to the order of several μV. The load cell component choice will provide a more thorough comparison.

The ADC presents the most freedom with respect to component choice. In favor of cost and utilization, a large bit ADC is not viable. Using a 32-bit ADC would be overkill compared to a 14 or 24-bit ADC. Using the same linearization approach, an 8, 14, and 24-bit ADC result in a least significant bit of 19.5 g, 0.305 g, and 0.298 mg respectively. The expected measurement of dry food is on the order of 60-100 grams. Either the 14 or 24-bit ADC would be sufficient.

3.2.3 Water Pump

Water pumps are classified into two categories: positive displacement and dynamic pumps. A Positive Displacement Pump operates by trapping a fixed quantity of fluid and pushing, or displacing, the trapped volume into a discharge pipe or system, whereas Dynamic or Kinetic pumps impart velocity and pressure to fluids as they pass through the pump impeller and then converting some of the velocity into additional pressure.. This pump works by increasing the velocity of the liquid and converting it to pressure in a diffusing flow channel. There are several different types of pumps within the two categories as fallows. [57]

Positive Displacement Pump:

Positive displacement pumps are divided into rotary, reciprocating, and linear configurations.

Rotor based pumps require very close clearances between the rotating pump and the outer edge, making it rotate at a slow, steady speed. If rotary pumps are operated at high speeds, the fluids can cause erosion. This eventually causes enlarges clearances that liquid can pass through, which reduces efficiency and the lifetime of the component. The following list defines three common rotary pumps:

- **Gear pumps:** A simple type of rotary pump where the liquid is pushed between two gears. Commonly used in hydraulic fluid power systems.
- **Screw pumps:** The internals of this pump involves two screws turning against each other to pump the liquid. Commonly used in irrigation and agricultural machinery for transporting grain and other solids.

- **Rotary vane pumps:** Shaped like scroll compressors, these have a cylindrical rotor encases in a similarly shaped housing. As the rotor orbits, the vanes trap fluid between the rotor and the casing, drawing the fluid through the pump. Commonly used in high-pressure hydraulic pumps and in automobiles systems such as: supercharging, power-steering, air conditioning, and automatic-transmission pumps.

Reciprocating type pumps move the fluid by using one or more oscillating piston, plungers, or membranes(diaphragms). Each period the valve restrict will restrict fluid motion to the desired direction. For suction to take place, the pump must first pull the plunger in an outward motion to decrease pressure in the chamber. Once the plunger pushes back, it will increase the pressure chamber and the inward pressure of the plunger will then open the discharge valve and release the fluid into the delivery pipe at a high velocity. Below are common reciprocating pumps:

- **Plunger Pumps:** A reciprocating plunger pushes the fluid through one or two open valves, closed by suction on the way back. (This type of pump is often used to transfer municipal and industrial sewage)
- **Diaphragm pumps:** Two diaphragms move in and out to fill the pump chamber with fluid and then push it out. When the diaphragms move away from the chamber, it lowers the pressure of the chamber and fluid rushes in. When the diaphragms return into the chamber, increases the pressure which allows fluid to flow out. The fluids flow through one-way check valves, ensuring that fluid only flows in the proper direction through the chamber. Diaphragm pumps are so versatile, they are used in virtually every industry that requires fluid transfer[131]

Linear positive displacement pumps displace the fluid with a linear behavior. Below are common linear pumps:

- **Rope pumps:** A rope pump is a type of pump in which the main component is a continuous piece of rope, which raises water from a well. Rope pumps are often used in developing areas, the most common design of which uses PVC pipe and a rope with flexible or rigid valves. Rope pumps are cheap to build and easy to maintain.
- **Chain Pump:** A water pump in which several circular discs are positioned on an endless chain. One part of the chain dips into the water, and the chain runs through a tube, slightly bigger than the diameter of the discs.

Dynamic Pump

Centrifugal Pump: A rotating, machine in which flow and pressure are generated dynamically. The energy changes occur by virtue of two main parts of the pump, the impeller and the volute or casing. The function of the casing is to collect the liquid discharged by the impeller and to convert some of the kinetic (velocity) energy into pressure energy.

For a centrifugal pump to work properly, you need to fill it up with water. Primary is required, because the pressure developed by the propeller of centrifugal pump, is proportional to the density of the fluid in the impeller. If the impeller is running in air, it will produce only a negligible pressure. This pressure will not suck water from the source through the suction pipe.

- **Axial Flow Pumps:** High flow, low pressure pumps which lift fluid in a direction parallel to the impeller shaft.
- **Mixed Flow Pumps:** Medium flow, medium pressure pumps which push fluid out away from the pump shaft at an angle greater than 90 degrees.
- **Radial Flow Pumps:** High pressure, low flow pumps which accelerate fluid along the impeller blades perpendicular to the shaft.

Special Pumps:

- **Cantilever Pump:** Centrifugal pumps with long cantilever design used in sump pump applications.
- **Jet Pump:** Kinetic pumps with an ejector attached at the discharge outlet, utilizing the Venturi effect and motive fluid to generate pumping pressure.
- **Turbine Pump:** Centrifugal pumps which use pressure in combination with a rotary mechanism composed of numerous small impellers and vanes to transfer energy to fluid.

Pumps specifications: The following specifications will be of focus when choosing a suitable pump.

- **Pump design:** Pump type.
- **Voltage:** Required input voltage.
- **Priming:** The preparation of something for operation.
- **Rated and Normal Flow Rate:** The expected volume of water per unit time the pump is designed for. The normal rate is often less than the rated flow and represents the conditions the pump is expected to operate at most of the times.
- **Suction lift:** The distance from the pump center line down to the free level of the liquid source below the pump
- **Total Head or pressure:** The total dynamic head of a water system must be considered when determining the size of pumping equipment to be installed. It determines the various head losses that the pump must overcome. Total dynamic head = elevation head + friction head loss + pressure head.

- **Pressure Switch:** A device that monitors pressure and provides an output when a set pressure is reached. The specific pressure that opens and closes the switch is called the set point. Many residential pressure switches are designed for a minimum of 30 PSI a maximum of 50 PSI.
- **Ports:** Point of connection.
- **Housing:** The substance from which the most outer layer is constructed

After extensive technological research, it was determined that the positive displacement diaphragm and the centrifugal pump would be suitable technologies for pumping the necessary volume of water to keep our felines hydrated throughout the day.

Both pumps are food grade, have a low flow rate, a compact design, and are cost effective. The mechanics, performance, and efficiency, gives and advantage to the positive displacement pump. The fact that displacement diaphragm pumps are self-priming distinguishes them from centrifugal pumps. Therefore, when diaphragm pumps are used, the water reservoir may be placed anywhere, but the centrifugal pump requires the tank to be at a considerably greater height from the pump for it to prime. The displacement diaphragm pump provides the freedom to build a more compact water system. Furthermore, if the user failed to refill the water reservoir, there would be no problem since diaphragm pump can run dry without overheating.

	Mechanics	Performance	Viscosity	Efficiency	Inlet Conditions
Centrifugal	Pressure is created and flow results.	Flow fluctuates as pressure changes	Efficient decreases with increasing viscosity due to frictional losses inside the pump	At higher or lower pressures efficiency decreases	Prime Needed
Positive Displacement	Flow is created and pressure results.	Flow is constant as pressure changes	Efficiency increases with increasing viscosity.	Increases with higher pressure	Prime's itself

Figure 10: Centrifugal and positive displacement pump principles.

3.2.4 Motor

The Purrfect Cat Care system requires a few key functionalities in order to fulfill the objectives set forth in the preliminary sections. These objectives include precision and accuracy, high response time, adequate torque, and affordability. The module that is responsible for the delivery of food pellets belong to the food station. This module must be consistent in its delivery if the user is to observe reliable data from the system. If the system produces varying results, the objective of providing feeding data loses all meaning. There are a few options available on the current market, Servo motors, AC motors, DC motors, and stepper motors. Since there are numerous options to choose from, it is reasonable to select from some of the most relevant to the project objectives. Sifting through the options available, it is quickly determined that Servo motors do not provide the precision required to deliver food to the bowl. They offer a quick and easy solution to dispense via a rotating axle but do not have a reliable means to break and hold a position. AC Motors are traditionally used in manners that require long operation, like pumps, water heaters, ovens, etc. While this may prove a useful component, it isn't quite specialized enough to accommodate the delivery of food in a consistent and precise manner. The remaining relevant selections to choose from include Servo motors and Stepper motors. In the next few segments, a discussion of servo motors and stepper motors will be explored in order to determine the best fit to realize the objective of precise dispensing amounts and accurate measurements.

Servo motors are electrical devices that rotate based on positional feedback through the use of sensors, this allows higher precision. Since servo motors require some sort of feedback system in place to effectively manage the rotation work done on some load, it requires more components for it to be effective. Based on the applications of Control systems this feedback circuit must compensate the deviation from the output in order to make the necessary adjustments to meet preset values set by the input.

There are a few types of Servo motors that potentially may meet the requirement of driving a load from a reservoir to the food bowl. AC and DC servo motors operate on the how the power supply turns on the servo motor. For a DC motor, supply voltage applied to the terminals of a servo motor determines the speed at which the rotation takes place given any constant load. This means for higher voltage inputs the higher the speed of rotation. Conversely, AC servo motors operate on the premise that the speed is determined by the frequency at which the voltage is applied. A second distinction between servo motors include varieties that are brushed versus brushless. Through the use of brushed servo motors, soft conductive metal sweep the walls of a commutator generating an induced current to set the motor into operation. Brushed servo motors are typically easier to operate and are less expensive. Brushless on the other hand are generally more expensive are more efficient and are less noisy. The final consideration includes the category of servo motors that relate to it being synchronous versus asynchronous. These terms pertain to the speed at which the rotor rotates with respect to the stators rotating magnetic field. When these two components are rotating at the same rate, the motor is said to be a synchronous motor. Asynchronous motors are often called induction motors and typically operate with the rotor lagging the stator's rotating magnetic field. The degree at which the asynchronous effect is pronounced depends on the number of poles or even the frequency of the input signal.

The operation of servo motors includes a feedback system which ends up being the adjusted input to the motor until a comparator makes the distinction that the error is zero. This means that the operation of the motor continues until a sensing unit can determine if the desired position or measurement has been reached. If this sensing unit determines the error is very large, the input to the motor is proportionally large. This continues persistently as to return the entire system to an equilibrium governed by zero error.

Although these are basic overviews of typical servo motor design additional insight into the construction of the motor itself does not contribute to a potential decision towards its use. Servo motors in its design operate in a similar fashion as stepper motors, but have a large focus on a close-loop design which requires feedback to adjust changes to the output with respect to the input. When these changes are zero, it is said the system is at equilibrium and no operation is required to use the motor. Since servo motors require an additional component to aid in the control of the device it may limit its effectiveness in the current design.

In this section, a discussion on the types of stepper motors that are available for this project. The Purrfect Cat Care system will have a food reservoir that has a dispensing mechanism that requires torque to turn an axle.

A stepper motor is one type of motor that might be consider for the design. This item is an electric motor composed of a rotor, and a stator that operates using a DC input. A rotor, a permanent magnet or a variable reluctant iron core is a freely moving part positioned at the center of the motor and aligns with the stator which is the stationary part of the motor. The stator is a fixed structure that has several windings that enable the generation of magnetic field lines in order to align the rotor to its fixed position. When current flows through the windings of the stator, this generates a magnetic field. Stators are found in series where one stator may be 180 degrees from the second stator, this is considered one phase of the stator circuit. Stator phases are dependent on their arrangement, this forces an alignment of the rotor to this fixed position. When done in sequence, the rotor may align to any angular position depending on the number of stators, or steps.

The number of stators, speed of the rotor, and torque are dependent on the construction of the stepper motor. Since a stepper motor is made up of two components, there are two design parameters that require integration, the rotor and the stator.

Rotor design is one characteristic to be considered, like a permanent magnet rotor design, variable reluctance rotor design, and hybrid rotor design.

- **Permanent rotor designs:** offers good torque and detent torque, the amount of torque required to overcome turning resistance. Although this is similar to the concept of inertia in which a force is required to overcome the tendency of an object to remain at rest, detent torque pertains to residual magnetism in a permanent magnet. As a result, permanent magnet rotors play a factor in the form of holding torque even when the stators are off. A disadvantage of this design results in lower resolution and speed.

- **Variable reluctance rotor designs:** offers higher resolution and faster rotational speeds but suffer lower torque and offer no detent torque. Due to this fact, variable reluctance rotors will not be considered since the scope of the project is only concerned with higher torque and a lower pulse rate, or the frequency at which the phases activate.

- **Hybrid Rotor design:** offers the benefits of both variable reluctance and permanent magnet designs. This means such designs maintain high torque, speed, and resolution. It is arranged in a manner where there are two caps with alternating teeth and is magnetized axially. One downside of such designs is that they are sometimes more difficult to construct, resulting in higher costs.

Stator circuits are an array of inductor coils arranged physically in series within the interior of a cylindrical shell. Logically these circuits may be wired 180 degrees from its opposite polar pair. The construction of the stator circuit dictates how the rotor aligns. The stator may be defined by the number of phases (coils of teeth) and pole pairs (number of teeth that occupy a phase) as well as wire configurations.

A driver must be used in conjunction with a system controller to activate the phase cycles of the stators in order to rotate the rotor. A few driver types include step/direction, unipolar, and bipolar motors. Step/Direction utilizes the step and direction pins, outputs to a driver circuit, such that when activated the rotor steps when the step pin reads high. When direction change is required, the output to the direction pin changes state. Alternate considerations include Phase/Enable, Pulse Width Modulation Voltage Control, and Current Control. These are common ways to interface with the rotor through the use of a driver circuit.

In order to produce these outputs, a specific arrangement of the driver circuit must be organized in order to deliver sufficient current to the terminals of the stators. Unipolar and Bipolar Motors types allow for control of current direction and even effect the change in current. One of the coils leads of a unipolar motor is connected to the input voltage. The activation of one MOSFET or the other drives the direction of the current from Vin to A+ or A-. Bipolar motors incorporate 4 MOSFET circuits that help drive the current across the coils. MOSFET circuit 1 and 4 are active current flows from A+ to A- and vice versa.

The knowledge of bipolar versus unipolar motors offer a method to control the rotation of the rotor, however this may be extended further to describe how the rotor steps from one phase to the next. These are stepper motor driving techniques that classify how the ends of the rotor are walked along the circumference of the cylindrical shell. The first of these modes is, Wave Mode. This indicates that one coil, or a phase, is active at one time. This means that current flows from A+ to A- and aligns the N/S with North being closes to the coil. Once the next phase occurs, North rotates to align with the new active coil. The opposite occurs if the current is reversed. Full-step mode is another sort of mode. Adjacent phases are active at the same time in full step mode. This forces the rotor to be positioned at a 45-degree angle to both active phases, resulting in the rotor bisecting the two at any given moment. In addition to this pattern, when current is generated in a combination of different directions, (ie A+ to A-/B+ to B-, A+ to A-/B- to B+, A- to A+/B- to B+, etc) this rotates the rotor. Next, convenient mode is the Half-step mode. While full-step and wave mode share the angular steps of 90 degrees, half-steps use 45 degree steps in order to walk the rotor a full 360 degrees. This takes advantage of the use of having more arrangements in which the orientation of the rotor may exist within the stepper motor. This allows for a higher resolution than the previous two, however sacrifices some top end torque. Based on this concept of more phase resolution, microstepping allows for activating two adjacent phases in such a way, that a percentage of one active phase overcomes the magnetic field of the other until the higher current is driven through the second phase to overcome the first one. In other words, at a percentage (p) of Imax, the current flowing through one phase could be on, while (1-p) of Imax may occur in the adjacent coil. As mentioned in the half-step variant, microstepping offers faster speeds but lower torque in order to accommodate this transition across each phase. These stepper motors typically have many stators to fine-tune and control the seamless transition of the rotor between multiple stators within any given cycle.

When selecting a stepper motor, there are a number of parameters that must be considered. These parameters that are considered in this discussion are torque, voltage/current, goal of stepping, and size of motor. All have their respective considerations and must fall within a range of the specifications of the system, i.e. inertia mismatch, undersized motor, etc. Load requirements may be the most important factor of these considerations. A torque watch gauge can be used to evaluate the load to which the motor will be linked. Such a device can measure the force needed to move the end of a lever from one point to another. This measurement is useful to determine the size of the stepper motor needed to operate at low speeds. Although this is an important characteristic to consider, most stepper motors offer adequate torque for the project parameters.

Additionally, Inertia mismatch may be another characteristic to consider. This characteristic is simply the amount of energy needed to overcome the existing state of rest or linear uniform motion of the first system with respect to an external system. In other words, if a small object is used to push a massive load along a straight line, it will tend to require a large sum of energy to overcome the massive load's inertia at a state of rest. Coupled systems should have similar inertial characteristics to provide a seamless transfer of power. High inertia mismatch introduces a destabilized drive/load relationship, which lowers the system's ability to control how fast, accurate, and precise the system is for each execution. Ideally, proper load inertia to rotor inertia should not exceed one order of magnitude, since each step correlates to a pulse driven by a microcontroller. Should this mismatch exceed this value, the system could expect to lose timing, overheat, and/or stall. This characteristic implores the consideration of the size of the motor. Although there are plenty of stepper motors available, a motor of comparable size may have too much torque and instead of dispensing food in a controlled manner, the motor may chaotically dispense the food in an unpredictable manner. Conversely, an undersized motor may cause more thermal radiation due to high current draw as a result of a heavier load.

Next, voltage and current requirements should be considered in order to ensure the motor can handle the appropriate range in current spikes that may occur when dealing with a variable load or variable dispensing speed. According to Machine Design, the driver should output approximately 1 to 2 times the motor's rated current and handle the step pulses to rotate the motor at a specific speed. This metric is needed to account for the motor fundamentals of back electromotive force and various electrical time constants as argued by the authors at Machine Design. Finally, microstepping may be considered in order to output a controlled quantity. Since this project requires accurate and precise amounts of food, this could play a role in the design of the substation. The goal of microstepping allows for the smooth rotation of the rotor across the numerous phases while reducing vibrations and noise. However, as previously mentioned, as the steps increase within the motor, torque is sacrificed as a result.

There are some advantages and disadvantages of using stepper motors. These motors operate off the principle of current flow through an inductor. Once current flows, the generation of this magnetic field forces the alignment of the rotor as previously discussed. This insight grants the main advantages of stepper motors, in which depending on the current flow with respect to another active phase this aligns the rotor in a precise way. These methods refine the angle at which the steps occur, the number of steps per active phase pair, etc. In this way there is no need for a sensor to determine the angular position of the positive pole of the magnet since this would correlate to the active phases at any given time. This provides an ease in programming the motor that may require a pulse width modulation signal and a command to enable the motor. As mentioned before, as the number steps increase, the torque degrades. This means that the rotational resolution of microstepping gets worse as the number of steps increase, this results in a greater chance that the rotor may miss a step and offers lower torque per step. Finally, stepper motors draw max current at stationary positions. This offers poor power efficiency and may overheat the stators in the process if held for long periods of time.

3.2.5 Motor Driver

The term motor driver is synonymous with any external integrated circuit managing power delivery and control of a stepper motor. Many common stepper motors, while DC, require an alternating signal to be applied between phases. If the motor is two-phase, or four-phase proper signals at a sufficiently large power must be generated. Other factors such as unipolar or bipolar winding configurations will also drive the decision. To keep this section focused on specs, the following four factors will influence driver selection: 1. winding configuration 2. Maximum output current 3. Maximum output voltage 4. Number of phases.

1. The winding configuration is the first criteria since a unipolar motor behaves magnetically different from a bipolar configuration. Choosing a bipolar driver to work with a unipolar configuration would likely cause problems. In general, the chosen driver needs to be of the same configuration as the stepper motor.

2. After choosing a configuration, the maximum current and voltage must be determined. A 24V, 1A stepper motor requires a driver that can provide an absolute maximum current and voltage above 24V and 1A, respectively. This statement may seem obvious but choosing a driver with a typical output voltage and current in the needed range as opposed to the maximum value will improve the devices longevity.

3. Idle power draw, input signal requirements, and protective circuitry are other important characteristics to consider. The only mandatory specification for the design is the signal

requirements. Ideally the driver is controllable from a microcontroller. Hence, it is necessary to choose a driver which supports either 3.3 V or 5 V logic control for the chosen microcontroller. Care also needs to go into current draw from these logic levels. Various microcontrollers have different maximum GPIO current. It is unlikely that a logic input would draw more than 20 mA, but it is a consideration none the less. The idle power draw and protective circuits are optional features that would be beneficial if the driver supported them.

4. The number of phases is important but not a critical decision. Critical is used in the sense of a 2-phase motor could be used with a 4-phase driver. Care is needed to ensure the proper phase from the driver is applied to properly activate the motor. Choosing the incorrect phase, a small error, is unlikely to damage the motor but will result in no motion. From a utilization perspective, using a 4-phase driver would be wasteful but is an option. Care was being taken to provide maximum flexibility due to the ongoing semiconductor shortage.

3.2.6 Flow Sensor

As previously stated, the Purrfect Cat Care system is not intended to replace human interaction, but rather to inspire people to become more involved with their cats. A good example is the recommendation from William (Bill) Burkholder, DVM, PhD, DACVN, and Charlotte Conway, MS, from the Food and Drug Administration's Center for Veterinary Medicine that pet owners should not only wash their pet's food bowl with hot soapy water after each meal and water bowls every couple of days, but they should also wash their hands before and after handling their pet's food to help prevent contamination.[44] Using the experts' advice, it's beneficial to include a functionality that allows the user to do so. A clever way to integrate this functionality is to develop firmware that can detect whether the bowl is present, enabling the user to clean the bowl as many times as necessary. Because the weight of the bowl is known, this would be the ideal time to calibrate the load cell. The system will then start its calibration and not take any readings until the calibration is complete. In addition, another approach to assure accurate readings is to potentially add a flow sensor that monitors how much water is dispensed during the day and compares its data with the load cell; if a delta is found, the system will recalibrate itself accordingly.

A water flow meter is a device that measures the amount of water that flows through a pipe. Several water flow meter technologies are available for selection based on the water measurement application, budgetary and space constraints. The following are the most popular types of water flow meters: mechanical water flow meters, ultrasonic flow meters, vortex volumetric flow meters and magnetic meters. Each of these water flow meter types has a distinct operating principle, total cost-of-ownership, and application benefits.[15]

The Mechanical Flow Meter is built with internal moving parts which may not fit with specific applications such as dirty water that carries large particles that may cause damage or obstruct the internal parts. The liquid flowing through a pipe causes the rotation of the internal moving parts (paddle wheel or propeller) which creates a flow rate that is proportional to the rotational speed of the internal paddle. Therefore, the faster the paddle is rotating, the more flow going through the pipe which in turn, sends a graduated signal to the controller. Many variables are taking in consideration as piping size, water temperature, etc., all go into a formula that will correlate the rotational speed with a unit measurement such as gallons per minute.

Mechanical Meter Type	Positive Displacement	Liquid PD	Piston	Gear & Lobe	Helix	Hall Effect	Turbine Flow
Best for:	Viscous Fluids	Resedential Water Metering	Viscous Fluids	Food & Beverage Processing	Cold Portable Water Bulk Flows	Air & Gas	Gas & Liquids

Figure 11: Compares mechanical meter and their substance of operation

For a Magnetic Flow meter or Mag meter to properly work the measured liquid must be water based or conductive. Mag meters are volumetric meter that have no moving parts which is why they are used in areas where exposure to the measured liquid is not desire while working on the meter. This makes the megameter a great choice for wastewater or process water that is consider fouled or dirty. The way a mag meter works is based upon Faraday's Law (E = B x L x V), where the signal voltage(E) is dependent on the average velocity(V) of liquid times the strength of the magnetic(B) field times the length(L) of the conductor (this is the distance between the electrodes). When a conductive liquid flows across the magnetic field of a flowmeter, a voltage is produced. The higher the voltage signal created, the quicker the fluid flows. The voltage signals are picked up by electrode sensors positioned on the Flow tube walls and sent to the electronic transmitter, which analyzes the signal to determine liquid flow.[58] There are three common types of magnetic flow meters.

Mechanical Meter Type	Insertion Magnetic	In-line Magnetic	Low-flow Magnetic
Best for:	Large pipes	High Accuracy and Flow Rates	Low-flow

Figure 12: Show the type of magnetic meters and their applications scenario

Ultrasonic flow meters measure flow velocity in a non-contact manner. They are clamp-on devices that attach to the outside of the pipe and allow the measuring of corrosive liquids without causing sensor damage. There are two types of ultrasonic flow meter, doppler and transient. The Doppler ultrasonic flow meter works based on the Doppler Effect, which is the physical phenomenon of a sound wave's frequency shifting. When reflected by suspended particles or gas bubbles (discontinuities) in motion, the frequency of an ultrasonic signal varies (Doppler Effect) in direct proportion to the velocity of flow of the liquid. On the other hand, the transit time ultrasonic flow meter measures the time elapse between the transmission of an ultrasonic signal from the first transducer and the reception of the same signal by the second transducer. The measurement from upstream and downstream are compared. The travel time will be the same in both directions if there is no flow. When flow exist, the sound will travel faster if is moving in the same direction and slower if is moving in the opposite direction.[59]

Vortex flow meters are quickly becoming the flow technology of choice for measuring gas, liquid, and steam flow. Vortex flow meters are suitable for measuring saturated and supersaturated steam in big facilities in order to enhance the efficiency and allocation of steam production. Vortex meters use a dimensioned bluff, sometimes called a shedder bar, to generate the phenomenon known as Kármán vortex street in which vortices begin to form and oscillate. The natural frequency of these oscillating vortices is translated into a digital signal using several sensor technologies, which is then processed by the meter's electronics to compute flow.

3.2.7 Liquid Level Sensor

The Purrfect Cat Care system would feature a water reservoir with enough water for at least seven days for our adorable friend. While designing the water system, the team realize that our system needed mechanism to alert the user whenever the reservoir is running low on water. Not having a way to monitor when the reservoir is running low could potentially lead to having the cat without water since the user could forget to check if the reservoir needs water. This will defeat the purpose of having an automated system to dispense water. The water system is design to take reading from the load cell multiple times per day to determine if water is needed, if the load cell request water when the reservoir is empty it could damage the water pump or flow sensor since they will be operating without water. Moreover, the data gather during these intervals can alter the cat's drinking behavior data which can affect the overall view of the cart's health which is the goal of the Purrfect Cat Care system. Consequently, it's essential to include a water level sensor that would alert the user when the reservoir is 80% empty, either by a flashing red light or an LCD screen display. This feature would increase the system's effectiveness since it would always alert the user when it's time to refill the reservoir.

Choosing the correct water level sensor might be difficult owing to the abundance of alternatives on the market. It is critical for the team to find an innovative and smart level sensor that is cost effective, durable, accurate, and easy to install. Because the system would just dispense water, there will be no need to search for a level detecting technology that works well with difficult substances such as sticky fluids and foam[32]. To select the appropriate sensor for this specific application, it is necessary to first understand the various technological alternatives, as well as their benefits and limits. The following are some of the most often utilized level sensing methods today's standards.[135]

The Optical Level Switches has a simple mechanism composed of two main components. An LED and a phototransistor that are housed within the sensor enclosure. When the sensor tip is in the air, the infrared light inside it is reflected to the detector. When immersed in liquid, the infrared liquid is refracted out of the sensor tip, resulting in less energy reaching the detector. Since these tiny devises are solid-state, it makes them excellent switches for a wide range of point level sensing applications, particularly where dependability is critical. [32]Optical liquid level switches can detect high, low, or intermediate levels in virtually any tank, large or tiny. The main advantages of optical sensor are their compact size, their lack of moving parts, and their low cost.

A capacitive level sensor operates on the principal of a capacitor. Capacitor store energy in form of an electric field between two conductive plates of certain shape with a certain distance between each other. By inserting a dielectric material between the electrode's an electrical field can accumulate when a voltage is applied between these two plates. As a dielectric liquid is introduced between the electrodes of the capacitor, the capacitance changes proportionately and liquid level can be determined. Capacitive sensors are ideal for solid, liquid, and mixed materials but they need to be calibrated for the material being measure. And not having a consistence material can affect the measurements.

The ultrasonic calculate the duration and intensity of high frequency sound waves reflected off the surface of the liquid and back to the sensor were the time required is proportional to the distance between the sensor and the liquid. These types of sensors have the same characteristics as lasers and are more adaptable in terms of installation and output. On the other hand, the range is less than that of lasers, and alignment of the emitting/detection and reflecting components is equally important. The technology of the ultrasonic sensor is suitable for a wide range of liquids, although performance suffers when used with foam.[135]

The Microwave/Radar sensor functionality is similarly to the ultrasonic, although the pulses travel at the speed of light. It sends out waves that are reflected to the receiver. The reflected waves are analyzed by the receiver. For example, if there is a moving item in the room, these waves will shift. The microwave detector can detect changes from one second to the next. The receiver should ideally be getting the same waves repeatedly. These types of sensors are commonly for security due to their ability to detect movement through walls. The downside is there not economical, and they accuracy can be affected by the environment. [32]

The vibrating or tuning fork sensor works by sensing movement like an earthquake or a mechanical failure in an industrial setting. It accomplishes these measurements by the amount and frequency vibration in each system. These sensors are ideal for keeping an overall health check on equipment since allows you to track down the root source of the vibrations and subsequent damage.[109]

Conductive sensors are used to detect conductive liquids at the point of contact, such as water and susceptible to corrosion liquids. To put it simply, two metallic probes (one long, one short) are inserted into a canister. The long probe transmits a low voltage, the second shorter probe is cut so the tip is at the switching point. When the probes are in liquid, the current flows across both probes to activate the switch. One of the advantages of these devices is their safety due to their low voltages and currents. They are also simple to use and install, but regular maintenance checks are required to ensure that there is no buildup on the probe; otherwise, it will not function properly.

Float switches are one of the most cost-effective and time-tested methods for measuring water

Type of sensor	Solids	Liquids	Hazy	Clear	Sticky/Foam	Cost Effective	Calibration
Optical Level	No	Yes	Yes	Yes	No	Yes	Yes
Capacitance	Material Dependent	Yes	Yes	Yes	No	Yes	Yes
Ultrasonic	Yes	Yes	Yes	Yes	No	No	No
Microwave	No	Yes	Yes	Yes	Yes	No	No
Vibrating	Yes	Yes	Yes	Yes	Yes	No	Yes
Conductivity	No	Yes	Yes	Yes	No	Yes	Yes
Float	No	Yes	Yes	Yes	Material Dependent	Yes	No

Table 3: Most common sensor technologies and their applications

level. A float switch is made up of a magnet within a float and a magnetic reed switch inside a safe enclosure. The float moves with the change in liquid, causing the reed switch to open or close depending on whether it is in air or liquid. Despite its basic form, this technology provides long-term dependability at an affordable price.

Following thorough technological investigation, it was determined that the optical liquid sensor would be the optimum sensor for monitoring reservoir water level. One of the reasons is that it is not necessary to monitor the quantity of water available in the water reservoir throughout the day; rather, it is sufficient to know when the water level is low. The problem can be solved by strategically installing an optical level sensor near the water reservoir's 80 percent empty threshold to inform the user when the reservoir needs to be refilled. Because the water system is designed to function at ambient temperature, the sensor does not need to withstand extreme temperatures. Furthermore, due to the restricted area provided, the sensor must be compact and light wight. Also, the sensor housing material must be food-contact grade because it will come into touch with the water that the cat will be drinking, as well as cost-effective.

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Types of Optical Sensors		Optical Digital Range	Optical Industrial Range	Optical Idustrial Glass Range	LLHP (High Performance Range)	POS Range	OpticalBasic Range
Type	Digital	✓					
	Industria		✓				
	Industria Glass			✓			
	HP				✓		
	POS					✓	
	Basic						✓
Housing	Polysulfaone	✓	✓				✓
	Trogamid®	✓	✓				✓
	Stainless Steel			✓	✓	✓	
Tread Type	M10						
	M12	✓	✓	✓			✓
	1/2" SAE	✓	✓	✓			✓
	1/4" NPT	✓	✓	✓			✓
	1/2" NPT		✓	✓	✓		
	3/8" BSP		✓		✓		
	1/2"BSP				✓		
	1/2"BSPP					✓	
	3/4"-16 UNJF				✓		
Operating Tempearature	-25˚C to +80˚C	✓	✓		✓		✓
	-25˚C to +100˚C					✓	
	-40˚C to +125˚C	✓	✓	✓	✓		
	-40˚C to +140˚C					✓	
Supply Voltage	4.5 to 15.4V	✓	✓	✓	✓		
	12 to 28V					✓	
	8 to 30V		✓	✓			
	10 to 45V				✓		
	3.3 to 24V						✓
Output Type	Phototransistor						✓
	Push Pull	✓	✓	✓	✓		
	P-Type		✓	✓	✓	✓	
	N-Type		✓	✓	✓	✓	
	N-Type(fly back)		✓	✓			
	N-Type(10Ω pull-up)		✓	✓			
Output Logic	Low in Air	✓	✓	✓	✓	✓	
	High In Air	✓	✓	✓	✓	✓	
	PWM	✓					

Figure 13: Level sensor attribute comparison.

3.2.8 Proximity Sensor

An infrared LED and photodiode could be used as a transceiver to detect or keep count of passing objects. The goal of the proximity sensor is to detect when a cat has entered and left the litter box. Various other proximities sensors such as li-dar, radar, and ultrasonic waves do excist but are not optimal for this application. The decision to use an optical beam was made for two reasons: 1. the litter box is such an small space that using reflection-based techniques like ultrasonic waves would be difficult, and 2. IR diodes simplify the interface with the system controller.

An approximation for the volume of a litter box is on the order of 6000-8000 cubic inches, or 3.47 to 4.63 cubic feet. The litter box that will be used for the fabrication is midway at approximately 3.87 cubic feet, and the box features a plastic enclosure. Brief research has shown that the common 38 kHz frequency used in ultrasonic sensors cannot pass through common high density plastics. Using the sensor would cause an incredible number of reflections within the enclosure making detection difficult. If the top of the enclosure were to be removed detecting the cat would still be challenging due to their placement in enclosed spaces. The way the litter sits in the box, the geometry of the room the box is in, and of course the cat will vary how these waves reflect and are detected.

Another issue is the act of retrofitting a litter box with the sensor. Section 3.13 discussed the current market of automated litter boxes. Several of the currently available litter boxes cannot support adding an ultrasonic sensor within it. The boxes which involve large mechanical systems to move the entire litter box would be the most affected. It is likely that each device was designed with a typical and maximum weight the mechanical systems can support. However, adding unnecessary weight should be avoided to guarantee mechanical stability. Imagine if the litter box started a cleaning cycle and became unstable like a brick in a washing machine.

The hardware implementation of the transceiver will be discussed in later sections. What is pertinent to the component choice is the peak transmission & detection wavelength, the radiated intensity, modulation scheme, and power requirements. Many IR transceivers are used in television remotes, the IR diode is in the remote and the detector on the cable box. When a button is pressed on the remote a bit stream is sent over air to the detector. Instead of occasionally sending a bit stream, if the stream is always present, the lack of a received pulse indicates something has blocked the beam.

Peak transmission and detection is relevant only to the chosen wavelength used to create the optical beam. Using visible spectrum LEDs to detect the cat could be possible but difficult. Ambient light would increase complexity on the detection side. Shifting the focus to infrared light has the benefits of being invisible to the naked eye; for both humans and cats. As well as being filterable from ambient light on the receiver side. Hence any IR LED and photodiode with a peak transmission and absorption in the 900 nm range is preferred.

Radiant intensity is a quite substantial factor in choosing an IR LED. A balance is needed between the optical energy radiated from the device and the input current. For short distances on the order of 1-3 feet the intensity does not need to be extremely large. Choosing a high power LED would not only be wasteful but dangerous. There are many standards regarding laser safety but the same caution should be exercised with high-power LEDs. For example, if an eye were placed within a centimeter or two of the LED there could be potential damage. To the team's knowledge, it is unlikely the IR LED may cause damage, and the respective data sheet has not mentioned any such operating mode. Regardless, a conservative perspective with respect to optical power output was taken.

Not much can be documented regarding modulation scheme. An incredibly common application of IR transceivers are television remote controls. The IR diode is modulated to form a digital bit stream sent to a receiver. The modulation scheme is not a key concern since data is not being sent.

3.2.9 Humidity Sensor

The humidity sensor is the most theoretically challenging component of the design. The hope is that the sensor will be able to detect local changes in humidity and infer whether the cat has urinated or defecated. Only primitive testing may be done to verify the validity of the humidity sensor. Including animals in the testing of the project is strictly forbidden and using cat urine presents other moral issues. Aside from these various what-ifs, the humidity sensor should work due to urine being composed primarily of water.

There are several measurement definitions that humidity sensors use. The two most popular schemes are relative and absolute humidity, referred to as RH and AH respectively. Regardless of type the sensor aims at measuring the mass of water in some fixed volume of air. The relativity comes in to describe what the moisture content is being referenced too. Absolute humidity takes a direct measurement taking the ratio of the mass of water to a known volume; $AH = \frac{m}{V}$. Where m is the mass of water measured and V is the known volume being measured. Relative humidity places the reference as the maximum water content within the fixed volume at a given temperature [82]. For example, a relative humidity of 50% implies the volume current holds half the maximum water it can. The remainder of this section will be focused on relative humidity sensors due to their surprisingly large abundance compared to absolute humidity sensors.

Various techniques are available to measure humidity but they fall into three categories: resistive, capacitive, and thermal [118]. The three types, and their various advantages and disadvantages, will be presented in order. Resistance-based sensors rely on the principle that moisture affects resistivity. One topology includes a serpentine-like resistive structure composed of a low resistivity material deposited on a substrate. As moisture makes contact with the low-resistivity material the overall resistance of the structure is varied. An inverse relationship is typically present where a large moisture concentration decreases the structure's resistivity. The resistivity-based sensors are incredibly cheap, small, and do not require calibration. The main downside is that chemical vapors can degrade the sensor's substrate. Typically the trace material is inert, leaving the substrate to absorb potential unwanted chemicals. The humidity sensors would be exposed to significant quantities of urea which could potentially degrade the sensor.

Capacitive sensors are quite simple in that the captured moisture would be placed between two plates of a capacitor. While air is not typically used, one could imagine water droplets affecting the dielectric permitivity of the capacitor. One significant concern is the dielectric permitivity of the chemical composition of the air. The relative dielectric permitivity of water is approximately 80, whereas urea has a relative permitivity of about 3.5 [100]. If a capacitive sensor were chosen, care must be taken to ensure the urea contamination does not result in erroneous measurements. Although, the capacitive style sensors do have the advantage of not letting the air directly interact with the electrodes or substrate. A thin polymer dielectric is deposited on top of the substrate and contact. Again, care is needed to verify that the standard polymers used are not susceptible to degradation by urea or ammonia.

Temperature based sensors rely on a pair of matched, negative temperature coefficient, thermistors. One thermistor is typically kept in a hermetically sealed environment. The example structure given in [118] utilizes a nitrogen environment. The other thermistor is exposed to the relative environment resulting in a temperature differential across the two elements. The resulting resistance of the two thermistors is proportional to the absolute humidity. The value of the absolute humidity may be extracted by placing the two thermistors in a bridge structure and measuring the differential voltage across the terminals of the thermistors. The article claims that thermal conductivity sensors are preferable in corrosive environments which would resolve the issue or urea and ammonia contaminants. The key issue is that the measured air must contain significant concentrations of nitrogen. Luckily air, urea, and ammonia are nitrogen rich compounds making this a non-issue.

Of the cited articles, not much is given regarding specifications. For the purpose of the project, the main specifications involve the resolution of the measurement and the data interface. For reference,the major component distributors include specifications such as humidity range for relative humidity, output types to differentiate between resistive, capacitive, thermal, and digital output devices, accuracy, and sensitivity. These specifications will be important in the component choice.

3.2.10 System Controller

In order to implement the behaviors of each station, a system controller of some kind is needed. Because the project will require complex interactions with sensors, controllers, and wireless communication, simple combinatorial logic will not be sufficient. Additionally, since the project is still in prototyping, a controller that is easily modifiable is desirable. For these reasons, a microcontroller will be used to control the stations.

Microcontrollers have a few aspects that should be considered in selecting one for controlling a station. First is the computing power of the microcontroller. Other than wireless transmission, the microcontroller must be able to handle sampling sensors at high rates, and it must have enough memory to hold the firmware and any data it collects during operation.

The hardware contained on the microcontroller is also important. Internal timers, ADCs, and communication interfaces such as UARTs or I^2C busses are important for applications which require them. If the microcontroller does not have the hardware internally, it will have to be added externally, which uses up the microcontroller's I/O ports, increases space used on the PCB, and increases the cost of parts to be acquired.

The amount of I/O the microcontroller is capable of is also important. It must be able to interface with multiple sensors of varying types. Controlling them may require multiple GPIO pins, or multiple communications interfaces.

Finally, for ease of development and lower cost, a single microcontroller which can handle all of the stations is desirable. Different microcontrollers with different architectures require different hardware and software designs, which increases the complexity of the project and the time for development. All of these aspects must be considered when choosing a microcontroller for each station.

3.2.11 Wireless Module

One of the main functions of the Purrfect Cat Care is the transmission of data between the subsystems and the main base station, which will handle all of the data processing. In order to transfer this data from the substations, they will need to use wireless communication as they will not be connected by any physical medium to the base station. This also allows for the system to be easy to use and setup for the user in their space and there will be no wires to deal with.

Since The Purrfect Cat Care system will be used indoors in complex spaces such as bedrooms or living rooms which can average from 3 meters to 9 meters across, it is not feasible to simulate the exact propagation path and resulting loss in such a complex space because there may be obstacles which can block the signal's path. Therefore, overcompensating by assuming a maximum range of 30 meters through free space. According to the Free-Space Path Loss equation, over 30 meters at 2.4 GHz, there is a loss of 60dB.

$$L_{fs} = 32.45 + 20\log_{10}(d_{km}) + 20\log_{10}(f_{MHz})$$
$$L_{fs} = 32.45 + 20\log_{10}(0.030) + 20\log_{10}(2400)$$
$$L_{fs} = 69dB = 99dBm$$

Most WLAN 802.11b receivers have a sensitivity of around -80 dBm to -100 dBm, around 11Mbps, which is the data rate of the IEEE 802.11b standard. Therefore, any transmitter chosen must have a transmit power of at least $-80dbm + 99dBm = 19dBm$

The ESP8266 microcontroller has an on-board Wi-Fi radio that supports IEEE 802.11b. It has a receiver sensitivity of -91dBm at 11Mbps, and a transmit power of 20.5 dBm in 11b mode.

The Raspberry Pi uses the BCM43438 chip, which has a receiver sensitivity of -90.5 dBm, and a transmit power of 21 dBm for IEEE 802.11b.

Of course, a radio system does not exist isolated from the rest of the world. Interference is also a potential problem. Since we can't quantify the exact amount of noise in every possible environment, we will instead test our system in a variety of environments to ensure that it operates correctly. In the case that we cannot achieve reliable communication over the desired distances, we may choose to design or acquire a higher gain antenna, even a directional antenna.

3.3 Software

The software system will consist of three main parts. First is the web frontend, which will provide a user interface that will show the current statistics for the cat, and will allow the user to request updated information, change the amount of food dispensed by the food dispenser, and change the schedule of the food dispenser. Second, the backend API will be responsible for storing and retrieving all the data gathered from the subsystems' sensors and the user's configuration information into the database. Finally, each subsystem will have firmware that is capable of communicating with the backend API to access the database.

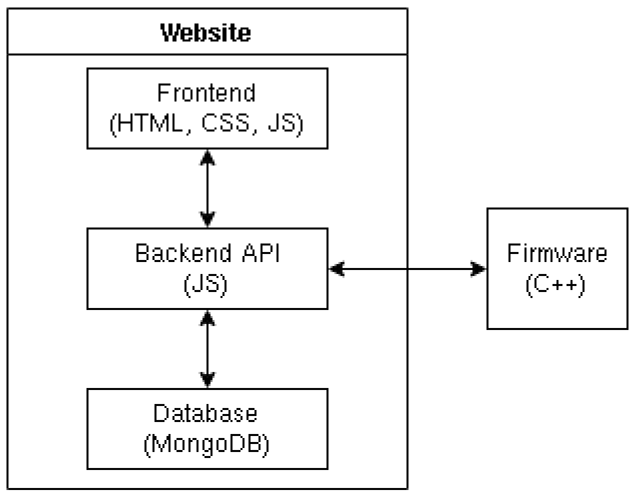

Figure 14: Block diagram for the software system

3.4 Website

To host the frontend, multiple options are available. Two major options for web servers are Apache and nginx. nginx is well suited to both large scale and small scale web use. Apache is also suitable for our purposes. Apache also provides Tomcat, a piece of software we could use to generate the dynamic content using Java. This could be helpful to the group since some members are familiar with Java already. If this is the software the group decides to use, Jakarta servlets can be written to handle requests from the website frontend, and service the user. [90]

Another piece of software that is relevant to the development of the webserver is Node.js. Node.js is a JavaScript framework built on Google's v8 JavaScript engine, used in the Chrome web browser. Node.js allows JavaScript code to run independently of a browser, and has a number of features that make it very suitable to the development of scalable network applications.

First, Node.js provides an event driven system using callbacks. This is built-in to the framework and does not require the use of operating system threads. This allows networking systems to be very efficient.

Second, Node.js removes most worry about deadlocking in parallel systems since very few IO operations are provided, and IO is designed to be rare. When IO does occur, it is handled in a synchronous manner to avoid deadlock.

Finally, Node.js provides native access to HTTP, which means that creating web servers is extremely easy. This would allow for easy integration of a Node.js backend with a frontend running in a web browser, since it is straightforward to send HTTP requests from a browser. [6]

JavaScript is an attractive choice for developing large parts of the application, since it can run in both the client and server. This could allow code-reuse, and a streamlining of the tooling needed to develop the application. It is also relevant that many real-world applications use JavaScript and Node.js, as opposed to the older Java servlet systems and other technologies.

3.5 Database

The database can also use a variety of technologies. Two currently under consideration are MariaDB and MongoDB. MariaDB is a database system designed to be as similar as possible to MySQL, so it is very compatible and therefore well documented. [5]

MongoDB is a ”NoSQL” database system that uses JSON-like documents to store data. It can be more flexible than SQL databases because it does not use a set schema for structure. This means that documents don't have to use the same structure, and new information can easily be added as the system grows. [88]

Both MariaDB and MongoDB can integrate with a variety of languages like Java, C++, and Python. MondoDB in particular integrates well with JavaScript, since it provides a library for easy access to MongoDB documents.

3.6 Operating System

For the operating system used in the base station, one option for the project is a Linux distribution. Linux is the operating system of choice for web server applications, running the more than 3 out of every 4 web servers on the public internet. [148] Linux is also compatible with personal computers, which would make development easier than using a less portable system.

Linux is also very well integrated with the internet as a whole, and has support for a wide variety of services, including DNS and DHCP, which will be important for this project since the base statuib must be able to resolve names and assign IP addresses to devices connected to it's network.

One of the most popular Linux distributions for servers is Ubuntu Server. Ubuntu Server has a number of features which make it an attractive choice. Ubuntu Server is extremely popular, so most software products have pre-built packages available for it or instructions on how to build for it. It has a powerful package management system in APT and Snap packages. It is also officially supported by Canonical, the large organization behind Ubuntu, and is designed for stability. [147]

The user will interact with the system through a website. They will access this website on their personal device after connecting that device. Since they will be on a private wireless network, the DNS services provided by the base station will allow them to easily connect to the website with a simple URL such as ”catcare.com” or some other memorable, simple phrase that can be printed on the physical station.

3.7 Firmware

The device firmware is responsible for collection information from each sensor and then sending it in the proper format to the database. The device firmware can be written in any language that supports a TCP/IP stack and can run on the microcontroller we choose. Some possible languages would be Java, C++, Python, or Rust.

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4 Hardware Component Investigation & Selection

This chapter addresses currently available products mentioned in Chapter 3. The differentiation from prior chapter was to keep the following information purely focused on product comparisons and the final choice. Throughout each subsection product features, specifications, and comparisons will be made. Each subsection will preface with the component chosen for quick access of component choice.

4.1 Load Cell

The TAL220B [141], 5 kg, load cell from HTC Sensors was selected as the force transducer for both the feeding and water stations. The load cell choice was a surprisingly simple choice due to a very limited market of products within the requirement specifications.

Several searches throughout the major component distributors for load cells and force transducers resulted in several pages of devices. Many of the products presented maximum rated force in units of pound-force. Surprisingly, the quantity of load cells in the 10 - 50 newton range were small; 2.25 lbf - 11.25 lbf. The conversion from newtons to measured weight involves dividing by 10. Hene, a 5 kg load cell can measure a gravitational force of 5 kg. The vast majority of load cells in the 1-5 kg range were compression, piezoelectric, and capacitive load cells.

Mentioned in chapter 3, the above load cell types experience substantial drift over time. Since the duration the food is in the bowl is unknown minimizing the drift, or creep, was the utmost priority. The two companies providing beam-style load cells were Loadstar sensors and HTC sensors. Loadstar emphasized in s-beam load cells. S-beam load cells have a pretty substantial height compared to parallel-beam load cells. The size coupled with a very expensive price tag eliminated Loadstar from consideration.

The only other option was the TAL series from HTC. Due to the lack of other suitable products, there was not much to compare the product against. The datasheet for the TAL presents error in terms of percentages of full scale. Some notable error percentages are:

- Combined Error: $\pm$ 0.05 % FS
- Non-linearity: $\pm$ 0.05% FS
- Creep: $\pm$ 0.1% FS per 3 minutes
- Ultimate Overload: 150% FS
- Input Resistance: $\approx 1k\Omega$

Errors such as zero balance, hysteresis, and repeatability are not substantial concerns. A net weight on the order of 0.5 kg at most is unlikely to cause issues with hysteresis and repeatability.

The zero balance of the scale can be addressed with microcontroller callibration. The combined error is somewhat ambiguous since the combined error of the entire system is lower than several of the errors composing the combination. Regardless, the error is small enough percentage wise that for the purpose of being a scale is more than sufficient. Slightly important, the ultimate overload allows a rare edge case of additional weight being dropped on the cell. The primary reason for 5 kg opposed to 1 kg is that a cat can weigh more than 1 kg. If the cat were to step on the scale and break it, albeit rare, is a possibility the design must address.

Refer to the component characterization section for information and figures validating the behavior of the load cell. Prior to purchasing the device the numbers seemed too good to be true. In the case that the error is larger than expected, several issues can be solved with calibration. Calibration will be discussed in more depth in the following chapters, however, creep error can be minimized with continuous calibrations throughout the day. Overall, the TAL220B should be an appropriate, cost-effective, and accurate load cell for our purposes.

4.2 Load Cell Amplifier

The Texas Instruments®ADS1231®24-bit Analog to Digital Converter for Bridge Circuits [3] will be used to condition and digitize the load cell's differential output signal. Two approaches were discussed in digitizing the weight measurement: 1. The HX711®by Avia Semiconductors [2]and 2. the ADS1231. The following paragraphs will discuss why the decision to use the ADS1231 was made.

As mentioned in Chapter 3, many strain gauge load cells are modeled electrically by a Wheatstone bridge. The two strain gauges measuring tensile forces are modeled by a pair of resistors. Likewise the two strain gauges measuring compression forces are also modeled by two resistors. For our weight measurements compression forces will be the primary focus. The fundamental physics behind strain gauges leads to differential voltages on the order of mV and μV which must be amplified before passing it to an ADC. Omitting this amplification would increase the complexity of the design due to this μV quantization.

Investigation into the data sheets for various load cells provide a parameter called, Rated Output. Rated output is given in units of millivolt per volt; $\frac{mV}{V}$. Depending on the excitation voltage, the voltage provided across the Wheatstone bridge, the differential output voltage may be larger or smaller. For a load cell with a 1 $\frac{mV}{V}$ rated output and an excitation voltage of 5 V the maximum differential output is 5 mV. Detecting a 5 mV difference over a dynamic range of 5 kg is not trivial. Hence, most load cells recommend placing the differential output to a preamplifier and ADC integrated.

The key factors driving the decision between ADCs were the ground-referenced maximum analog voltage, the common-mode rejection ration (CMRR), and the full scale differential input to the device. For HT Sensor Technologies^{TM} TAL220B load cell, the typical excitation voltage is between 3 to 10 V. The rated output is approximately 1 $\frac{mV}{V}$ after disregarding the error bars.

To maximize the sensitivity of the device an excitation voltage of approximately 8 V will be used. This 8 V excitation results in a 4 V common mode voltage to be present at the ADC. As well as a maximum differential voltage of 8 V at full scale.

The table below provides device specifications for the HX711 and ADS1231. The specifications are provided before the discussion to provide comparable arguments for the devices.

Specification:	HX711	ADS1231
Analog V_{DD} (AV_{DD})	2.6 - 5.5 V	3.0 -5.3 V
Digital V_{DD} (DV_{DD})	2.6 - 5.5 V	3.0 -5.3 V
Common-mode Rejection $(CMRR)$	-100 dB	-110 dB
Maximum Ground Referenced Analog Input	$AV_{DD} - 1.3V$	$AV_{DD} + 0.3V$
Noise	50-90 nV_{rms}	35 nV_{rms}
External Reference Required	None	None
Built-in Regulator	Yes	None

Table 4: HX711 and ADS1231 specification comparison chart.

From the table above it is clear that the HX711 and ADS1231 are nearly identical. The primary differences between devices lies in the external circuitry required to drive the device, where the bridge interfaces with the device, and the maximum ground-referenced analog input voltage. Ultimately the maximum analog input is what chose the ADS1231 to be chosen over the commonly used HX711.

Beginning with the drive circuitry for both ICs, the HX711 has a built in analog voltage regulator. The built-in regulator is very reminiscent of linear regulators such as the 7805 and 7815. The base of a pass transistor is controlled by the IC allowing input power pass to the output. A resistive divider is in parallel with the load cell to provide a feedback mechanism. As for the ADS1231, the IC does not have a built-in regulator. The external analog and digital voltage supplies must be generated externally. The external power generation does have the advantage of utilizing a more efficient buck converter to generate the supply rails. However, the HX711 does have the advantage of lower component count if an external regulator were used.

The data sheet for the HX711 leaves something to be desired. Compared to the ADS1231 there is not as much information regarding device implementation, interfacing with a system controller, and the structure of the output data stream. The ADS1231 addresses all of these issues and even provides data on the noise characteristics, something which will would have been useful if the accuracy was not sufficient. Outside of technical specifications, TI is a well respected company and makes many great products. We feel confident as a team that any issues we had could either be resolved by the product's data sheet or their in-house customer support division.

4.3 Pump

The market offers a variety of options when it comes to diaphragm liquid pumps. The table below displays a comparison of the main electrical characteristics of AE1207, AJK-B4009 and FP 70 DC pumps which are one of the most used in the industry. The FP 70 DC it's available in three difference types of voltage where the as the others are only available at 12V.[96] The FP 70 DC can be custom fit to basically any project that requires a micropump. It has an integrated damper that provides smooth flow with low pulsation, low flow resistance inside the tube and prevents bubble formation. Also, it comes with a digital customizable motor for precise flow control and pinpoint adjustments to electronics that will be interface with. On the other hand, the AE1207 requires the least amount of current as a result its power consumption is way less than the other two pumps.[143] In addition, it offers the lowest flow rate which in this application its beneficial to have a lower rate since the application requires small amounts of water to be dispense in a timely manner. Unfortunately, the AJK-B4009 offers the highest flow and the second highest power consumption.[7]

Specifications	AE1207	AJK-B4009	FP 70 DC
Volts (V)	12	12	12
Curent (mA)	300	<500	650
Relative Hummidity (˚C)	<80%	<80%	<80%
Teperature	0-40	-	5-40
Flow rate (ml/min)	0-100	1500	1200
Power Consumption (W)	3	7.5	7.8

Figure 15: Pump specification comparison.

When their dimensions and cost are compared, the AE1207 is the most compact of the three, making it perfect for the water station.[143] The three pumps are bidirectional, which is not necessary for implementation but is useful for testing because it can move water back and forth without reconfiguring our setup, reducing the possibility of damaging other adjacent equipment. The AJK-B4009 is the most cost effective, but as previously stated, it has the greatest flow rate, which is not desirable for this application.[7] The FP 70 KPDCB-4B provides excellent water flow and accuracy but at a huge cost. Therefore, to regulate the accuracy of the water flow, the water pump will be used in conjunction with the water flow sensor. Consequently, the team chose the AE1207 because of its low power consumption, compact size, and inexpensive cost.[96]

Dimension and Cost	AE1207	AJK-B4009	FP 70 KPDCB-4E
Driver size	27.6 X 37.9 (mm)	30 X 36.5	56.55 X 48
Pump	31.7 X 20.1 (mm)	39.7x35	141 X 48
Pump head (m)	25	35	40
Pump suction (m)	5	9.5	6
Bidirectional	✓	✓	✓
Price	$9.89	$5.60	$150-$300

Figure 16: Physical dimension and cost comparison.

4.4 Flow Sensor

Following an extensive technical examination of a variety water flow meters as seen hardware investigation section, the team decide to look at one more type of sensor. The Hall Effect water flow sensor is combination of a mechanical and magnetic sensor. This sensor is usually made from a plastic valve through which water can flow. A water rotor and a hall effect sensor are used to sense and measure the flow of water. When water comes through the valve, it causes the rotor to spin. The motor's speed would fluctuate depending on the rotational speed of the rotor. The spinning of the rotor induces a voltage differential in the sensor. This induced voltage difference is transverse to the electric current. Current passes via the hall effect sensor between its Vcc and ground pins. The changing magnetic field applied due to the rotor, it interacts with the magnetic field of the running current, deflecting electrons to one side and causing a charge imbalance across the chip. The hall voltage is caused by a voltage potential differential across the sensor caused by one side of the sensor having more electrons than the other. The stronger the magnetic field, the more electrons in the hall effect sensor are deflected, and the higher the voltage potential generated. As a result, the rate of flow of water may be determined.

Although Hall Effect sensors are usually seen as more expensive than typical linear or rotational sensors, this is not always the case, and they are frequently chosen for their advantages. They are highly reliable, provide high-speed operation, can operate in a broad temperature range, and have pre-programmable electrical angles and outputs. Furthermore, the Hall Effect sensors do not wear and so have a long life. Below is a comparison of a few Hall Effect sensors that appear to be extremely appealing for use in the water system.

According to Figure 17, the YF-S401 [84] can operate at 5V DC with a higher operating current then the 173935-C-FT-110 [146]. Even though the CNK IFM offers a +/- 15% input voltage tolerance, it is not required because the supply voltage would be 5V with a very minor variance. Providing the proper voltage would result in the flow meter operating at peak efficiency and producing consistent data. Water pressure isn't an issue because the application only requires

Hall Effect Sensors	YF-S401	173935-C-FT-110	CNKB IFM-8
Working Voltage	DC 5- 24 V	DC 5 - 24 V	DC 5V ± 15%
Working Current	15mA (DC 5V)	8 mA	-
Max Water Preassure	116.03 (psi)	200 (psi)	7.25 - 145 (psi)
Load Capacity	≤10mA (DC 5V)	20mA	-
Operating Temperature	≤80˚C	-20-100˚C	-
Liquid temperature	≤120˚C	≤100˚C	0 - 30˚C
Storage Temperature	-25~+80˚C	-25~+80˚C	< 40˚C
Error	±5%	±3%	±10%
Flow Rarte	0.3 - 6L/min	1 - 25L/min	0.3 - 2.0 L/mim
Frequency variation	± 10%	-	± 10%

Figure 17: Show electrical specifications comparison

Product Feature	YF-S401	173935-C-FT-110	CNKB IFM-8
Stainless Steel Impeller	✓	✗	✗
Anti-leakage	✓	✓	✓
Food-grade	✓	✓	✓
ROSH	✓	✓	✓
Compact	✓	✓	✓
Cost	$9.49	$167.00	$3.60

Figure 18: Characteristics comparison

small volumes of water to be dispensed. Therefore, the YF-S401 psi values are enough. The working temperature of all three flow sensors is comparable, however the YF-S401 has a more appropriate range for indoor use, which is where the water system would be housed. Although the YF-S401 has a little higher error % than the 173935-C-FT-110, it is 16 times less expensive, and the error can be overcome using firmware. The pump would be working at roughly 1 L/min, which is within the range of all three flow sensors, however the CNKB IFM-8 lacked a comprehensive datasheet, which was a deal breaker. The 173935-C-FT-110 meets all the requirements, but at an exorbitant price. Furthermore, all three sensors have the same characteristic, except for the YF-S401, which has a stainless-steel impeller, making it a more durable sensor. Therefore, the YF-S401 meets the specifications, features, and cost-of-ownership requirements for this application.

4.5 Fluid Level Sensor

Analyzing the below table, which compares the most economical optical sensors in the industry, it can be established that the optical digital range is the suitable sensor that checks all the boxes.

This digital sensor is built of food-grade materials such as Polysulfaone or Trogamid. It also has three tread kinds and a room temperature working temperature. The sensor may be powered by a 4.5 to 15.4V supply voltage and has a push pull output as well as three distinct output logics.

Optical Digital Range Sensor	LLC10100	FR-IR02	OLS2 M12
Supply Voltage (Vcc)	+4.5Vdc to +15Vdc	5Vdc	+4.5Vdc to +15Vdc
Supply Current	2.5mA max	.5A	2.5mA max
Output Sink Source	100mA max	10mA	100mA max
Operating Temperature	25˚C to +80˚C	-25˚C to 120˚C	25˚C to +80˚C
Storage Temperature	40˚C to +125˚C	-40˚C to +125˚C	40˚C to +125˚C
Preassure	7bar(101 psi) max.	5 bar (72.5psi) max	7 bar(101 psi) max.

Figure 19: Electrical specification comparison.[99, 98, 120]

According to the comparative tables below, the FR-IR02 has a slightly higher power consumption than the other two sensors, but it has a wider operational temperature range. The all three sensors have the same storage temperature range and similar pressure limitations. When comparing the characteristics or features of all three sensors, the FR-IR02 is five times less expensive than the most expensive sensor in the comparison tables. Because all three sensors are relatively close to one another, with only the price separating them, the team has opted to utilize the FR-IR02 to monitor the water reservoir of the water station.

Product feature	LLC10100	FR-IR02	OLS2 M12
No mechanical moving parts	✓	✓	✓
High reliability	✓	✓	✓
Small (less then 25 mm long)	✓	✓	✓
cost	$50	$10.49	$43.12
High precision	✓	✓	✓
Installled any direction	✓	✓	✓
RoHS	✓	✓	✓

Figure 20: Product attribute comparison

The liquid-level sensor is installed using the side Installation mode and link it to the following circuit: the signal end will output a level signal corresponding to the water level, which is accessed as a liquid-level control signal to the MCU A/D port or other control circuits. When the liquid level is above the critical liquid level and the sensor body is submerged, the signal output is low voltage; when the liquid level is below the critical liquid level and the sensor

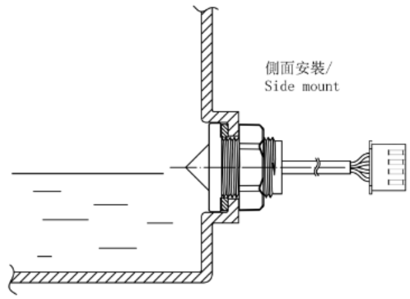

Figure 21: Sensor positioning diagram.

body is exposed, the signal output is high voltage. Specific parameters are shown in the table below.[134]

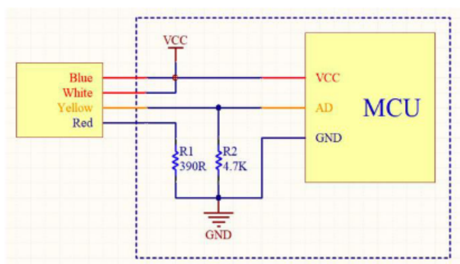

Figure 22: Sample circuitry.

In practice, the liquid level threshold voltage is set as VT, which means that if the output voltage of the signal end is higher than VT, the liquid level is decided to be lower than the critical liquid level; and if the output voltage of the signal end is lower than VT, the liquid level is decided to be higher than the critical liquid level. The value of VT is chosen between 0.3 and 0.5 V, and the precise value is decided by the pace of dirt formation. If the fluctuation is considerable and the fluctuation range is greater than 1MM, the anti-shake logic should be introduced to the program. The surface of the sensor becomes filthy over time owing to liquid contaminants; however, this has no effect on the sensor's function unless dirt covers the entire surface of the sensor. These types of sensors are extremely sensitive when exposed to direct sunlight, since the sensor will be in an enclosed location there will be no faulty readings.[134]

Liquid Level	Outout Volatage of Signal Output(V)	True Value	Total Current (mA)	Power Dissapation (mW)
Above Critical liquid level	<0.1	0	<12	<60
Below critical liqud level	>4.6	1	<12	<60

Figure 23: Working parameters at room temperature.

4.6 Motor

The WO-417-11-18 Hybrid Stepper Motor by Lin Engineering®will be used to drive the mechanical dispensing mechanisms [149]. The motor is a 24V 0.6A stepper with a 0.9° step. The motor uses a bipolar winding construction with maximum holding torque of approximately 14 oz-in.

Similar to the load cell, not much was present to compare the motor. A brief search of the major parts distributors quickly revealed the dominance Lin has over the stepper market. The Lin website revealed a wealth of information regarding torque-frequency curve generation over power input, application notes, wiring diagrams, and much more. Perhaps a small bias was formed due to the friendly introduction into their products, how to use them, and any additional information we could need but it was decided early on to use a Lin product.

The Lin hybrid stepper motors are on the more costly side. At a price point of approximately $40 the motor is the most expensive single component. While $40 may seem a lot it truly is not with regards to the quality of the product. The motor has already been purchased and the construction is extremely high quality. Mentioned earlier, mechanical components nearly always fail before solid state components. Hence, spending a little bit more of the budget on buying a quality stepper motor with precise control was valid.

In addition the 0.9° step provides some freedom in achieving the desired accuracy. For example, to accurately dispense 60 grams with a 2% error requires a maximum of 1.2g be lost. The small step shifts the primary source of error to the mechanical dispense. Depending on dispenser designs the error could even be shifted to an individual piece of dry food. Having precise accuracy in a pet feeder may sound like overkill, however, there are pet owners who need to have their pet on a strict diet. Whether it be for preventative or prescribed reasons having precise control over the amount of food being dispensed is ultimately a benefit.

Specification wise, Lin provides a torque-frequency curve plotter. Converting ounce-force-inch to metric units, the maximum 14 ozf is equivalent to approximately 10 newton-cm. It is extremely unlikely the dispenser will require a torque of 10 N-cm. Luckily the Lin stepper can be run at input power much less than the recommended 14.4 watts; 24V 0.6A. Throughout the dispensing mechanism prototyping experimentation can be done to determine a relatively efficient input power to achieve sufficient torque. Relaxing the power requirements will also simplify the design and specifications of the power supply.

The 42BYGHW811 by Wantai Motor offers a 2.5 A/phase at a step precision of 1.8°. As with most stepper motors, this motor is commonly used for the purpose of CNC machines. This is a four wire bipolar stepper motor, with a holding torque of 4800 g-cm.

In contrast to the Lin Engineering component, Wantai Motor's W811 offers much higher torque at the cost of higher amperes per phase. Given this, the design of the PCB would have to account for larger traces in areas where the motor is directly connected. Unlike Lin Engineering's website, a reliable data sheet has not been readily available for the W811. Fortunately enough, the popularity of this model has been high, resulting in multiple instances of data regarding testing, parameters of operation, etc.

The W811 is a much more affordable component pricing in under $20. Although this is much more affordable than the WO-417-11-18, it still is the single most expensive component yet to implement into the design. At the time of this entry, the WO-417-11-18 had been previously purchased and tested only to be found insufficient for the needs of the design. In a later section, these reasons will be discussed on page 89.

The step precision of the stepper motor, offered by the W811, increases to 1.8deg. This seemingly degradation in step resolution still offers considerable control since, the speed can be changed in firmware, making up for the lack of precision. The 1.8° steps offer increase rotation speed over finite pulses that are to be generated by the microcontroller. This is important in order to meet the requirement specifications of the design since, a higher step resolution may result in longer dispense times.

Unfortunately, the W811 does not offer an interactive web page that allows for dynamic selection of the torque/frequency requirements. However, the motor in question does offer flexibility to be integrated in a variety of different systems since its electrical characteristics are common. For the purpose of the system design, it was determined that the rated voltage of 3.1 VDC falls within the window of what may be feasibly implemented by a variety of different stepper drivers.

4.7 Motor Driver

In the selection of an adequate driver for a Brushless DC motor, servo motor, or stepper motor, it should be considered how the load will be driven, for what duration, and how the load will need to be controlled. Although these are fundamental questions for choosing an appropriate motor, how the motor is to be driven also require these same insights. Given the design of the project, precision and accuracy are paramount in the delivery of the food pellets to the feeding bowl. For every dispensing action of the delivery system, the repeatability of every interaction should be consistent. Since it has been previously determined that the Purrfect Cat Care system will be using a stepper motor, selection for stepper drivers will be considered to operate in tandem with the W0-417-11-28 bipolar Hybrid Stepper Motor by Lin Engineering. In the selection of common driver integrated circuits, driver chips maintain some extensively elaborate designs. Many come with additional features that require firmware to adjust features that would otherwise be inaccessible or built-in features that support the normal operation of the chip. In terms of discrete components, most driver ICs operate off of the standard H-bridge design. Common implementations of H-bridge circuits include the use of MOSFETs for their innate characteristic to isolate current draw to a just the source and drain branches. For a circuit that may generate back-emf from the inductor, this may be preserve the life of the system. This segment covers Texas Instrument's DRV8428P [43], Lin Engineering's R208 [126], STMicroelectronics' STSPIN220 [105],and Allegro MicroSystems LLC's A4988 [**A4988**] which should fulfill the necessary current demands of the Hybrid Stepper motor.

The Texas Instrument DRV8428E/P Dual H-Bridge Motor Driver comes equipped with an integrated current sense and smart tune technology. These technologies offer the driver the ability for current regulation which spans a multitude of decay modes. This offers minimization of current ripple and being able to adapt to changes in the step tempo. This driver was chosen to offer the needed management of stabilizing the current being fed into the W0-417-11-28 Hybrid Stepper Motor by Lin Engineering. There are a number of different drivers offered on the market, but this particular product offers a few advantages over other products such as the R208 offered as a supplementary product to the Hybrid Stepper Motor within Lin Engineering's lineup.

Some basic requirements that the DRV8428E/P offers include the 4.2V-33V operating supply voltage range. This enables a number of different line voltages to be generated down from a wall line. The design currently requires the use of a 12V and 5V rail used to power the pump of the water station and the stepper motor for the food station. Additionally, this IC offers a sufficient output current to the stators in the form of 1A. This allows the flexibility to provide enough current to the stator windings of the stepper motor, since the current per phase is approximately 0.6A. Finally the driver has the ability to reach microstepping quantities assuming the frequency of the input does not exceed 100kHz. Due to availability the only models offered are just the DRV8428P models, which imply that the operation of the chip will be based on a pulse-width modulation signal driven from an adjacent microcontroller.

Besides the baseline requirements, notable benefits of this model include a current regulation feature that operates to account for large changes in current and helps maintain the current through the stators to ensure smooth and accurate operation. In the event that operation of the motor generates a large surge of current, the current sense feature works to regulate the current levels and prevent further damage to the rest of the circuit. A final consideration, includes the chips low power mode feature. Since a majority of the time the food station will remain at an idle state it would be extremely wasteful for the system to be operating at normal power for long periods of time. This would mean that current is flowing through the stators of the stepper motor keeping the rotor held in place. While in this mode it is extremely wasteful to have this operation for a majority of the day. Low power mode still offers functionality to the carrier board and chip, however it does so at a much lower output current to the stators, approximately 2μA.

STMicroelectronics' STSPIN220 driver IC is a modest alternative to the previous two driver ICs in that it offers the same baseline characteristics required to run the Hybrid stepper motor, but with less features. Some key characteristics are the fact that this driver may operate at in low voltage settings that are ideal for battery powered sources, which may even operate in a zero-consumption state. The energy saving features may be maintained by battery and a standby consumption less than 80nA. The ideal environment for this device includes pop-up camera control for smartphones, point of sale (POS) devices, portable printers, etc. The STSPIN220 does support 256x microstepping and is supported with documents to enable this feature much like TI does for the DRV8428P. Final acknowledgements include circuitry that supports full protection from short circuits, thermal damage, and current overload. Since the driver has a footprint of (3x3x1)mm, which is of equivalent size to the DRV8428P it proves to be a viable option to implement into the existing design.

Allegro MicroSystems LLC's A4988 DMOS Microstepping Driver offers current protection, an output drive capacity up to 35 V and +/- 2 A [**A4988**]. Much like the aforementioned components, I also falls within the prescribed range of 3 V to 12 V as a voltage load. Although it does not meet the parameters of the Lin Engineering model W0-417-11-18, it does meet the specs necessary for the W811, since its current per phase demand falls around 2 A/phase. Additionally, it should be noted that the logic supply voltage range is 3 V to 5.5 V. Since microcontrollers typically output 3.3 Volts peak, a PWM signal produced by the controller would require a modified circuit to account for the small change from voltage low to voltage high, (i.e. 3 V, required by the driver, and 3.3V, being the possible max amplitude produced by the controller.). The implementation of the driver chip included a carrier board by Pololu. The use of this carrier board comes equipped with the A4988 as a packaged set making the driver circuit implementation easier to integrate into the actual design. Since the complexity of the entire system requires attention on several fronts, the need to develop a design to house this driver was not required.

4.8 Optocoupler

Typically choosing an optocoupler to isolate a system controller and the downstream circuitry is trivial. A microcontroller has a maximum output current which prevents the controller from adequately powering the circuit. Each of the major component suppliers have pages and pages of optocouplers with identical 50 mA output currents with approximately 10 mA input currents. However, when the driving circuitry requires much larger current draw the decision becomes less trivial. The chosen pump and motor have input current draws on the order of quarter to half an amp. To resolve this current requirement, the ISOCOM 4N32 optocoupler will be used.

Ideally, the output drive current would be the major component decision. However, most general purpose optocouplers have current transfer ratio (CTR) of approximately 100% to 500%. Assuming the best case scenario of a 20 mA input current, only 100 mA will be seen at the output. Many optocouplers also have an absolute maximum collector current of 150 mA. Trying to squeeze every ounce of performance to increase the input current would degrade the lifetime of the device. Trying to find an all-in-one device with our needed current capabilities is not possible. The hardware design section will address the current amplification techniques, but a Darlington-output optocoupler was needed.

Three products were considered for the optocoupler: 1. The Fairchild FOD3120 Gate Drive optocoupler [65] 2. the Fairchild MOCD223M Darlington output optocoupler [115] and 3. The ISOCOM 4N32 optocoupler. The table below lists some general product details driving the decision and a more explicit description will be provided after.

Beginning with the FOD3120 Gate Driver, this product was found based on the output current capabilities. The driver is able to source up to 2.5 A on a digital signal. As name suggests, the device is intended to drive the gate of high-power MOSFETs and IGBTs. Using the device as an optocoupler would work but the output current is incredibly large. In the schematics later in the report, the optocoupler is simply driving the gate a MOSFET with a load in the order of 250 mA. Being able to supply such large current to the gate of the FET was deemed too much. Instead, a more moderate optocoupler would be preferable.

The MOCD2XXM series of optocouplers are general purpose devices. The CTR depends on the model chosen but is a maximum of approximately 200% with the MOCD207M. This CTR should be sufficient in supplying enough current to properly saturate the transistor but the advantage is in the number of channels. This optocoupler is housed within an 8-pin SOIC package. Instead of leaving two pins as no connect Fairchild opted to include a second coupler. The second coupler theoretically doubles the current transfer ratio. If the two couplers are placed in parallel with the load and the same input current is driven through the two input diodes then nearly identical currents will be seen at the output. At the time of investigation, this part was out of stock in each of the major distributors and it was chosen to find another optocoupler.

Lastly, the ISOCOM 4N32 was chosen as the preferred optocoupler. Originally the 4N32 from Vishay Semiconductors was found, but due to supply chain issues they were out of stock. The product by ISOCOM features similar specifications and was deemed good enough to sufficiently isolate the system controller and the pump. Some notable properties of the device include up to 1000% CTR, 5 to 100 μs turn-on and turn-off time, an open-base to allow for additional passives which improve stability, and a darlington output increasing the possible output current. After comparing the datasheets of both models by Vishay and ISOCOM, it seems that ISOCOM has significantly improved the performance of the chip.

4.9 IR Transceiver

Transmitter

The Vishay TSAL4400 High Power Infrared Emitting diode will be used to create the infrared beam composing the proximity detector [83]. The device is marketed as high power, however, it will operate under more conservative power draws. The choice of a high power transmitter was to provide flexibility in the Radiant Intensity specification. The design expects a standard litter box which has an width on the order of 1-2 feet. Designing he transciever to properly transmit over a meter will ensure that any form of litter box may be used, and that reducing the power can be done to meet the 1-2 width.

The table below compares the specifications of the TSAL4400 with a similar product, the NTE30047 by NTE electronics

Specification	TSAL4400	NTE30047
Half Angle	20 deg	20 deg
Max. Forward Current	100 mA	800 mA
Radiant Intensity @ 20 mA I_F	8 mW/Sr	20 mw/Sr
Duty	N/A	0.01 ms

Table 5: Infrared transmitter specification comparison chart.

From the specification above, it would seem that the NTE30047 is without a doubt an improvement on the TSAL4400. Yes, optical power output was a key concern but the modulation scheme is as well. As mentioned throughout the technological investigation, IR receivers typically operate at 38 kHz. In the datasheet for the NTE30047 no mention is given to rise or fall time. The TSAL4400 features rise and fall times on the order of 15 ns, allowing for 38 kHz signals to pass through it. The NTE30047's specification of a 1 kHz duty is not clear if it refers to the maximum frequency the transmitter will pass or if it is the typical frequency the specifications are taken from. Regardless, the tradeoff in optical power for timing was deemed more important and Vishay offered many other models of transmitters in the TSAL product line.

Receiver

The TSSP5838 from Vishay semiconductors will be used as the receiver photodiode [89]. Although not written in order, the receiver was chosen first to find an accurate power requirement on the transmitter. Many receivers found support a digital-like interface. When optical energy saturates the detector the detector outputs a high voltage. Inversely, if the optical beam is blocked then a logical low is present. Throughout investigation the TSSP line from Vishay was found and there were difficulties finding other non-Vishay products to compare against. The list below provides key specifications on the TSSP5838.

1. Up to 2 meter proximity sensing.
2. Receives 38 kHz modulated signal.
3. Photodetector and preamplifier in one package.
4. Low supply current.
5. Visible light suppression.

The most important of the above features is the proximity sensing, the included preamplifier, and visible light suppression. Typically a litter box is indoors and away from any sources of natural light but the included sunlight filter only increases the accuracy of the detection. The 2 meter sensing ensures the beam will be detected and at a considerably lower irradiance than other receivers on the market. The preamplifier presents a convenience factor due to simplifying the output interface. A fun stretch goal would be to design the transimpedance amplifier by scratch but due to time constraints the preamplifier provides the necessary signal conditioning without extensive circuitry.

4.10 Signal Generation

Two options were considered regarding signal generation, the time-tested LM555 Timer and the LM567 tone decoder [103, 104]. The final implementation will utilize the LM555, however, if supply chain issues were not present the LM567 would be chosen.

Beginning with the LM567, it may seem confusing that a tone decoder could be utilized as an oscillator. The 567 operates on the principle of passing the input signal through a passband filter that switches a logic output. Tones which fall outside of the passband result in a logic low at the output. Similarly tones within the passband will pass through to the output. If it were possible to internally generate variable frequency tone within the IC then the output could switch between high and low states. Inserting a capacitor from ground to the input pin will generate such signal. One external resistor and capacitor are necessary to tune the frequency to the desired signal.

The component minimization was a driving force in using the 567. A 555 timer operating as an astable oscillator typically includes two capacitors: one for the CV pin and one for the charge/discharge network. Two resistors and a diode forming the other half of the charge/discharge network. Sparing three components may not seem significant, however, soldering the components onto compared to the 555 is the primary reason behind choosing the 567.

4.11 Humidity Sensor

As stated in the technological investigation, the humidity sensor is subject to testing in order to determine the feasibility of urine detection. The AM2320 Humidity and Temperature sensor from Adafruit Industries was purchased as a low-cost and quick prototype sensor [40]. The device features an I^2C bus which transmits both the temperature and humidity every 2 seconds. Yes, two seconds is a significant delay but it is short enough to gather several samples before the cat finished. The datasheet provides sample firmware and a library to simplify the device prototyping progress. The device measures relative humidity to an accuracy of 3%, and requires a 3-5 V bus to power the device. Being provided sample firmware will make the prototyping process incredibly quick as to not devote too many resources to one component test. The accuracy a 3% is not fantastic but should be good enough for initial testing. Not much additional information is given about the device or it's construction.

It was acknowledged by the team that more appropriate sensors exist on the market. However, in the early stages of the design it was unsure if the humidity approach to detecting urine would be feasible. Again, it is believed that the approach is valid because urine is predominantly composed of water. For a proof-of-concept implementation the AM2320 is sufficient and investing the time to properly compare current devices on the market was not deemed an effective use of time. Further implementations and improvements of the project could address a more precise, or longer-range, humidity sensor to provide more creative algorithms for detecting urine or excrement.

4.12 Microcontroller

Under consideration for controlling the water, feeding, and waste stations were three microcontrollers: the MSP430, ATmega328P, and the ESP8266EX [**ATmega328P**, 114, 62]. The MSP430 by TI is a 16 bit MCU, and we are all familiar with its operation. The ATmega328P is a popular, low cost MCU. However, neither of these MCUs are well equipped for wireless communication on their own, while the ESP8266EX has built-in support for a full wireless stack, and does not require an external wireless module. The ESP8266 also has a wide variety of software available for it, including numerous Arduino libraries. For these reasons, we chose to use the ESP8266 for our stations.

Features that make the ESP8266EX attractive mainly comes down to the Wi-Fi features available. The standards that fall within the capabilities of this device include, 802.11 b/g/n as well as two virtual Wi-Fi interfaces, and have a frequency range of 2.4GHz-2.5GHz. In terms of the hardware, important electrical characteristics include an operating voltage range of 2.5V – 3.6V. For the given design currently in place, the power system will involve a wall line that will step down 24VAC down to 12VDC and 5VDC. From the 5VDC line, a breakout board will support the step down from 5V to 3.6V should the need arise. The power management characteristics of the ESP8266EX offers a decent power suite. Since the original design of the microprocessor is often used in IP cameras, security ID tags, smart plugs and lights, etc., built in features had to support efficiency of power consumption and energy saving technology. Features like light-sleep mode offers low power consumption by pausing the CPU and all peripherals. Although these features do not directly benefit the system since the entire system will be powered via wall line voltages, this does offer a benefit that could be explored in future applications.

The ESP8266EX supports two Serial Peripheral Interface (SPI) pins, which could potentially support the task of transmitting data from either the water station, food station, or waste station using a chip select (cs) pin allows the Master to individually select which device it wishes to communicate with at any given time. Since the data is not crucial to be delivered to the base station instantaneously, using this communication standard enables seamless communication between the master and slaves.

An additional supporting feature of ESP8266EX is I2C. The microcontroller supports one input and one output for data dedicated to I2C. The benefit of I2C is that error handling is higher than other communication standards through the use of acknowledge/no-acknowledge functionalities. The final communication standard that could potentially be used in the communication of data between the base station and the individual modules, is Universal Asynchronous Receiver Transmitter (UART). Although speed isn't of paramount concern when communicating data from modules to base station, UART isn't very effective in accomplishing the task of data transmission versus other alternatives.

In terms of features, final considerations acknowledge the use of Pulse-Width Modulation (PWM) and an internal Analog-to-Digital Converter (ADC). The PWM output interfaces provide usefulness to the project since for the food station, a PWM signal will be injected into a driver IC that runs the stepper motor. Given this insight, it offers a solution to this problem. The ADC that is integrated into the IC has no direct application to the project objectives but offers comparable features to the MSP430. The features outlined here are comparable to those offered by the MSP430FR6989 and the ATmega328P. As noted before, the deciding factor that separates the ESP8266EX from the latter two microcontrollers, is the built-in Wi-Fi capabilities.

4.13 Wireless Module

To accomplish this wireless communication, two wireless modules were compared for use in the Purrfect Cat Care subsystems and base station to transfer data wirelessly, The ESP8266EX and the ESP32-C3, both from Expressif [61].

Both of the chips are very similar in their specificiations so the discussion will focus on the differences found between the two models. One thing to note is that they both support several revisions of the IEEE 802.11 standard created by the Institute of Electrical and Electronics Engineers, including the b, g, and n revisions, discussed in a later chapter. Also, they both support transmission in the 2.4 GHz band.

ESP8266EX: This chip has an on board CPU that offers a large ROM capacity which will be useful for the modularity of the systems as it will hold the firmware for controlling the module. This also means an additional microcontroller will not be needed as this module can act as a microcontroller on its own, furthering the benefits of lower total costs. This module can also handle a large range of operating voltage and temperatures making it easier for integration with the other components. Additionally, the ESP8266EX has a variety of on board antennae to choose from which gives the project some freedom of choice between Wi-Fi and Bluetooth wireless communication [140].

ESP32-C3: Very similar to the ESP8266EX, this chip also has an on board CPU, however, it does not offer as much ROM. Although this chip does not have much ROM, it does have a large amount of RAM[139]. This adds performance in the module, however may not be as important since most of the processing of the data will happen on the base station. The benefit from the additional RAM results in the transmission of the data using the hosted API.

Below are the specifications for the two wireless modules under consideration.

ESP8266

Processor: Tensilica's L106 32-bit processor

RAM: 50 kB

ROM: 512 kB - 1 MB

Wireless: 802.11 b/g/n support

Wireless: 802.11 n support (2.4 GHz), up to 72.2 Mbps

Wireless: 2.4 GHz Receiver & 2.4 GHz Transmitter

Bluetooth: WiFi/Bluetooth

Power: 2.5V 3.6V, 80 mA

Temperature: -40 °C 125 °C

Antenna: PCB Trace, IPEX Connector, Ceramic Chip, or external

ESP32-C3

Processor: RISC-V 32-bit

RAM: 400 KB SRAM

ROM: 384 KB

Wireless: 802.11 b/g/n support

Wireless: 2.4 GHz Receiver & 2.4 GHz Transmitter

Bluetooth: Bluetooth 5, Bluetooth Mesh

Power: 3.0 3.6 V

Temperature: -40 105 °C

Antenna: PCB Antenna or external connector

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5 Software Component Investigation & Selections

Building on the research in chapter 3, this chapter outlines the selections made for each software component. The rationale for each decision is explained, and competing technologies are discussed to explain what was found deficient or inferior in them.

5.1 Programming Languages

Many programming languages were under consideration for our project, including Java, Go, and Rust. However, we have decided on using JavaScript for our website, and C/C++ for our device firmware.

5.1.1 JavaScript

JavaScript is a multiparadigm, loosely typed scripting language originally intended for use on webpages to deliver dynamic content. However, it has since grown to be a multi-purpose tool, and through systems like Node.js, it can be run independently of a browser. JavaScript can support functional and object-oriented programming. It is an interpreted language and therefore suffers the same performance issues as do other interpreted languages. However, its loosely typed syntax allows for quick and easy development of software. Additionally, its ability to be used in both client and server environments could be very beneficial in developing the frontend and the backend for the Purrfect Cat Care system. As one of the most popular languages being used today, there are many reference materials available to assist in troubleshooting and debugging. As an additional benefit, most companies look for JavaScript developers and could prove beneficial to become more acquainted with the language Although it is a good language choice for developing the web application and its backend, it is unsuitable for driver use as it does not have low level memory access capabilities.

JavaScript was chosen as the language to implement the web server in because it allows us to use Node.js. Node.js is a widely used, well documented JavaScript runtime environment that allows for the easy creation of both web frontends and backends. This was chosen over Java, which would be used as Servelets, because the environment is more modern, the language is more popular, and the setup is more straightforward. Servelets would require integration with a web server like Apache, which requires more complex configuration.

Though JavaScript does have downsides when it comes to organizing very large projects, we believe that it will not be an issue for Purrfect Cat Care since the backend and API are relatively small. The loose typing system of JavaScript will not be a problem for verifying functionality of the backend, especially when paired with appropriate testing frameworks such as Mocha and Chai. Additionally, for frontend development, many libraries and frameworks are available, such as React.js and Angular.

5.1.2 C and C++

C and C++ are high level programming languages with strict data structures and low-level memory management and compatible across most devices. The main draw of C and C++ is the extremely fast execution speed and small size of the compiled code. They are popular choices for small devices that are limited in storage and memory, and on platforms that require quick responses for complex operations and calculations. These programming languages are useful for low-level, procedural work. Additionally, the object-oriented capabilities of C++ make it suitable for large-scale development work. C++ also supports functional programming with the use of lambda functions. In the Purrfect Cat Care system, these languages would be used in the firmware programming of the subsystems. However, neither language is the best choice for user interfaces, since they do not integrate with servers like Apache and technologies like servlets and HTML as well as other languages such as Java or Python.

For firmware development, C and C++ were chosen because they are fast, well tested languages that we are all familiar with. A large variety of libraries compatible with the ESP8266 boards is available, and C and C++ integrate with the Arduino development environment, which is what we will be using for firmware development.

5.1.3 Other Languages Considered

The other languages considered are listed below, along with their advantages, disadvantages, and relevance to the project.

5.1.4 Java

Java is a high-level general-purpose programming language with a focus on portability by running on a Java Virtual Machine (JVM). The JVM sits between the lower-level hardware and the compiled Java code and is compatible with most operating systems. It also has built in garbage collection which gives greater freedom with data when coding. However, due to it running in a virtual machine and the automatic garbage collection, it is slower than ”bare-metal” languages like Rust, C and C++ languages. Java has object-oriented capabilities that make it suitable for large-scale development work. It is also highly suitable for work with user interfaces due to its ability to be integrated with technologies like Apache Tomcat, and it has extensive support of database integration. For example, Java works seamlessly with technologies like MySQL and MariaDB.

The most recent released standard for Java is the JSR-000392 also known as JavaTM SE 17 which details the specifications for the Java language, and the JVM.

5.1.5 Rust

Rust is a high-level programming language that is designed to be thread-safe with a focus on memory safety [77]. This means there is no built-in garbage collection because it is not needed. It is a compiled language that has speed comparable to the C language without the risk of memory leaks or scope loss and is therefore a reliable programming language. This is especially useful for embedded systems because of the importance to conserving and using memory efficiently on these smaller devices. It also supports object-oriented programming and is often used as a replacement for equivalent C and C++ code. Its extensibility allows the ability to be compiled to WebAssembly, so it could be integrated into a user interface and used alongside Javascript. One major drawback is the rigidity of the compiler which can make it difficult to get the code to compile once complete [77]. This requires very careful programming practices. Another drawback is that this programming language is rather new, which can make it difficult to find a solution when running into problems. Despite these drawbacks, its precise low-level access and speed make it a good contender for base station of the Purrfect Cat Care System as well as any of the subsystems.

There are no published standards for Rust.

5.1.6 Python

Python is a high-level, multiparadigm programming language. It has a natural syntax making it easier to understand than most other high-level languages but has high overhead due to being an interpreted language [158]. However, because it is an interpreted language, Python is platform independent and also easy to test because it does not need to be compiled and can be run easily many times in any operating system, as long as the interpreter with the same version is installed. Python is suitable for several high-level tasks and can also be used for networking, but it is not as suitable for writing device drivers. Due to its extensibility, Python can overcome its weakness in speed by integrating directly with other languages such as C and Java. Given its many plugins, Python can also be used in many different databases, meaning if this is the primary language chosen, an additional language would not be needed for the database. The Purrfect Cat Care System will have an application user interface for the base station. Python offers several solutions for developing frontends. First, Python offers QT and tkinter which are both frameworks for developing graphical user interfaces. Python can also be used for frontend web development for a web application. Finally, considering the statistical data analysis that will need to be done on the sensor data, Python is one of the top languages used for data analytics and therefore would be a good contender for processing the sensor data.

The most recently published version of Python is Python 3.9.7.The most recently published version of Python is Python 3.9.7. The main standards found for Python are the style guides, which define how to layout the code, for example the usage of spaces and tabs, as well as how to import libraries to name a few. The language is governed by the Python Software Foundation (PSF) and would be the place to go for best practices and coding standards.

5.1.7 Go

Go is a high-level open-source programming language developed by Google. It has strong support for concurrent programming and supports imperative and object-oriented paradigms. Go is a compiled language which supports compilation to native binary, WebAssembly, and JavaScript, so it could be useful for a variety of purposes, including frontend and backend development. It is based on C and Python, therefore it contains features from both languages. For example Go benefits from running comparatively fast like C and is also has a very easy to understand syntax like Python, making it easy to code in. One of Go's unique features is its omission of certain common features, such as inheritance and generic programming. Although, because the language is relatively new, there is not as much reference material available as there are for older more widely used languages.

The standard for Go is the Go Programming Language Specification, published on the official Go website.

5.2 Database

Under consideration for the database were mainly MySQL in the form of MariaDB, and MongoDB. We chose to use MongoDB for the following reasons:

1. MongoDB stores information in JSON, which integrates well with our JavaScript backend.
2. The structure of records is flexible, allowing us to quickly make changes as needed during prototyping. This is in contrast to SQL databases such as MariaDB, which are more rigid.
3. Libraries are available through NPM to easily interface with MongoDB through JavaScript.
4. We already have experience using MongoDB in JavaScript backends.

One difficulty we encountered in using MongoDB on our base station is that the most recent version does not support the ARM processor on our board. This was easily circumvented by using the previous stable version of MongoDB.

5.3 Operating System

Only a handful of operating systems were considered for use on the base station. The two main families to choose from for server architectures are BSD and GNU/Linux. Linux is more widely supported on the Raspberry Pi and most other single board computers, and one of the most popular and therefore compatible Linux distributions is Ubuntu Server. Ubuntu Server provides a stable, well understood environment that all popular software, including Node.js and MongoDB, will run on well. Official documentation for most tools is available for Ubuntu specifically, which makes setting up that software easily. In addition, Ubuntu itself is very well documented and supported by Canonical. For these reasons, Ubuntu Server was chosen to be the operating system for the base station. [87]

5.4 Web Server

5.4.1 Frontend

Front end applications can be authored as native apps or as web apps. A native application runs on a specific platform, such as a certain phone or computer, and needs to be installed to run. A web application runs on a browser, which is installed on many phones or computers. To make the Purrfect Cat Care system easy to run and distribute, the front end will be developed as a web application. There are many web application frameworks to choose from when authoring a front end. Each has its strengths and weaknesses which should be examined when finding the best fit to use for a project. Below, three different popular technologies for web application development currently used in the industry are examined for use in the Purrfect Cat Care system.

Angular is a frontend framework that is coded in TypeScript in an IDE and generates JavaScript code when run. This provides a strict programming environment that compiles down to a loose programming language, allowing the development of dependable code that also has wide support across devices. Angular is also focused on being compartmentalized into components that can be reused. The two libraries included in the framework RxJs and Angular Material will provide a smoother user-friendly experience because the calls to the backend will be relatively unseen to the user and the application can run faster [75]. They also provide the ability to develop a modern look and feel for the application layer, which also makes the user experience simple and smooth, both goals of the Purrfect Cat Care front end. All of these features put Angular in a strong position to create the front end for the Purrfect Cat Care system.

React is another powerful web application framework which was developed to create rich web applications that can support large audiences and rapid page updating. This framework was originally developed by Facebook to handle the large amount of data which it needed to display in a timely manner and features a virtual browser Document Object Module (DOM) that displays to browsers more quickly than its competitors. Even with these traits aside, React is a powerful tool for creating a front end that is dynamic and provides rapid development with reusable assets. React uses NPM to build, test, run, and deploy. It can also use the Create React App NPM package to create a new app with ease, making it very simple to get an application started and running within a short amount of time. React is written in JavaScript, but has an integrated language called JSX that allows the creation of page elements in a way that mimics the actual HTML being rendered [64]. This allows dynamic HTML elements to be containerized and to load data from JavaScript dynamically. All of these culminate in React being another strong contender for the Purrfect Cat Care system, but its main focus seems to be on commercial applications with larger audiences and larger data processing requirements.

jQuery is a large JavaScript library rather than a web application framework, but it is often discussed when web applications are chosen. jQuery extends and simplifies the functions of JavaScript to minimize the amount of code needed for common and complicated operations, while also taking away the focus of browser support, by handling that under the hood. jQuery is extremely useful when compared directly to JavaScript, since locating elements and doing mass updates or animations can take dozens of lines of code, while jQuery can perform the operation in a single line of code. Because jQuery is not a true framework, it offers the complete freedom to perform any function that you could do in plain JavaScript, but in a way that is far more efficient and many times less verbose. This helps write lightweight and stable applications, but requires that the developers have a strong grasp on JavaScript making it more useful for experts in the using the language. Also, due to being a library rather than a full framework, more coding needs to be done overall with jQuery than with one of the frameworks listed above, simply because the frameworks provide more scaffolding to assist in creating applications, by assuming and limiting the development in a way that saves time on delivering the final product. jQuery is classically used for small web projects or by developers who have a strong grasp on JavaScript and jQuery itself. Therefore, its candidacy on whether it will be a good candidate for the Purrfect Pet Cat system highly depends on the skills of the team that will be building the application.

In assessment of the technologies just discussed, it was decided that an Angular Web Application front end will be the ideal choice for developing the application layer for the Purrfect Cat Care system. Because Angular seems to be built to be more stable than React and also provides an environment to assist the developer in creating an application, this will work well with some of the constraints the team will be facing, discussed in a previous section.

5.4.2 Backend

Behind the user interface of the Purrfect Cat Care system's application as well as the communication between the different stations is a backend that will handle relaying data and updates between all the different systems. For this backend, there are many languages and configurations that could be implemented to receive and transmit data.

The backend will be hosted on the base station using a Restful API. A Restful API uses an open JSON object format to transmit data, as opposed to a SOAP API which uses a stricter XML approach. Restful APIs are less verbose and have better backwards and forwards compatibility, as any unused fields are ignored. In addition to being Restful, this API will control the system passively through a series of responses, instead of actively by explicitly sending commands. For example, when the food station refreshes its feeding schedule, it does so by sending a request to the base station for the latest schedule. The response sent from the base station will contain the latest feeding schedule information.

The backend could be hosted in a number of different programming languages with varying strengths and weaknesses. Along with the languages, there are also numerous frameworks that exist which can help speed up development by providing prewritten libraries that handle standard functionalities. Taking advantage of these frameworks also helps prolong the life of the product, since the frameworks will continue to update their libraries to provide new features, compatibilities, and bug fixes which can then be easily integrated into the existing code with minimal changes.

NodeJS is a relatively new contender in the realm of frameworks, but one worth looking into for this project. NodeJS is coded in JavaScript, which is one of the most well-known and used languages in web applications. Due to the vast network of resources and knowledge-base available, there is a very low barrier to entry for learning to code in NodeJS [67]. NodeJS is also an easy to setup and run framework, using a tool to create, build, and deploy called NPM. The NPM command line tool can be used to easily create all the code for an empty project with all the libraries and dependencies, check the code for errors, run the code locally for testing, and create deployment packages. The language itself is touted to be event driven, and was one of the first popular non-thread blocking languages, meaning the processor threads are not devoted to individual messages, but instead they use a queuing system to run all of the requests and responses on demand so that the threads do not become "blocked" shutting down the API [67]. This is helpful for this project which will run three substations at one time all sending their updates frequently. This framework is built on a standalone core of Google Chrome which runs without a web browser, and handles backend calls from the server-side. This means that the browser and version of a client-side system do not matter, which will ensure compatibility, since the language is compiled to the widely adopted plain JavaScript. Taking into account all of these features, a NodeJS backend framework would make an easy to learn and is a reliable choice for the Purrfect Cat Care system.

Another backend framework under consideration is .NET Core pronounced "dot net core" is a framework that was built as a cross-platform version of ASP .NET, Microsoft's flagship framework. This high performance platform has wide adoption and support of its large community, including support from Microsoft themselves. Written in C# in the Visual Studio IDE, the Web API uses standards such as MVC (Model, View, Controller) to rapidly develop APIs using prebuilt templates [37]. Though this goes a step further in providing a starting point for rapid development, it does require extensive knowledge of the C# language to develop an API on this framework. The code is compiled down to machine code rather than scripted, which is why it excels in performance. That aspect combined with the scalability of systems running .NET Core, means that it is ideal for large API systems, such as a MicroService architecture, which uses a series of small modular APIs together to run a backend [10]. That makes updating any single point in the backend much easier since it is sectioned off from all the other services. Though these are all strong points for this framework, it deviates from the focus of the Purrfect Cat Care system which will only require a single lightweight API, so this framework offers too much overhead and barrier to entry for a project of this size.

Symfony API is a framework that can be used to build a backend in PHP. Unlike the other two stated above, this framework does not do as much assistance in getting a project started, and neither creates a project as a starting point, nor handles building and deployment. PHP, like NodeJS, is a scripted language, so it does not compile to run, and will work on any server that has a common gateway interface (CGI) installed on it [79]. This grants a great deal of freedom in the design and execution of an API, but also this flexibility can be a detriment when designing, since so many of the design decisions are not guided by well-known standards. Getting help for any coding issues or writing test suites could prove challenging due to how much each Symfony API project differs from each other. That being said, PHP is a language that has many resources available, and that can help in lowering the learning curve when getting into this language.

Weighing the API systems above, the ideal backend for the Purrfect Cat Care system will be a Restful API authored in NodeJS. Since NodeJS has a low barrier to entry and uses JavaScript, this will allow the team to write a backend quickly and easily given the time constraints on the project. NodeJS will also provide the proper handling of requests from the three substations which will be updating the base station with their sensor data throughout the day at possibly overlapping times.

5.5 Frameworks and Libraries

In order to create the backend and frontend, a variety of frameworks and libraries will be used. Frameworks are pre-made systems that provide standard functionality. The frameworks chosen are well-established, and provide speed, security, and reliability.

Libraries are collections of code that enable special behavior to be reused instead of created from scratch. Libraries are essential to writing code efficiently.

5.5.1 Express

Express.js is a general purpose web framework designed for creating websites and implementing APIs. It is minimal, but provides a wide variety of HTTP functionality. The team chose to use Express because it allows developers to focus on the API functionality instead of creating unique HTTP routes for all requests. Express provides a modular way to create ”middleware” applications that handle requests, facilitating high code reusability. This will allow the team to quickly prototype and finalize the backend API. [63]

Because of its minimal design, Express provides only a thin layer between the application and Node.js. This means fine control of the backend will still be achievable, and the able to use other frameworks and systems in tandem with Express is still possible.

5.5.2 Mocha

Mocha is a testing framework for JavaScript that can automatically run unit tests and integration tests. Using a testing framework is essential to develop parts of the system in parallel. Since not all parts of the system are finished from the beginning, a testing framework that allows mocking is necessary. In addition, if the project grows in the future, a testing framework already in place will allow easier growth. Mocha is a high quality, commonly used testing framework, and it allows both of these requirements to be fulfilled. Its features include asynchronous testing, and testing in parallel. [117]

5.5.3 Chai

In order to write tests using Mocha, a library of test assertions and vocabulary is required. Chai is such a library that provides assertions for both Behavior Driven Development (BDD) and Test Driven Development (TDD). Using Chai, it is possible to specify the required behaviors of every component of the backend API. Chai provides three primary interfaces, called ”should,” ”expect,” and ”assert,” each of which allow different types of BDD or TDD testing. In addition to basic Chai, Chai-HTTP will be used to properly handle testing APIs which use HTTP. Chai-HTTP adds vocabulary for testing various parts of HTTP requests and errors. [36]

5.5.4 MongoDB Node Driver

To connect a Node.js application to MongoDB, it requires the installation of a MongoDB Node driver. This driver provides an API that defines the different functions needed to connect to MongoDB, read from and write to MongoDB, and many more functions the backend needs to interact with the database. Not only does it have the basic access functions, it also has many options available for handling server outages, monitoring, and logging. This is useful for larger projects that require a guaranteed up-time. This driver is needed to manage the access to the MongoDB database from the backend.

5.5.5 Angular

Angular is a web application framework developed to quickly create stable web applications that function across a large variety of browsers. Angular uses a code generator, called Angular CLI for creation, building, testing, and deploying code. The output of Angular is plain JavaScript once built, but for development it uses an Integrated Development Environment (IDE) and is coded in TypeScript to prevent common JavaScript runtime errors [9]. Angular has two useful libraries that will assist in the development of the frontend app, RxJS library that executes asynchronous AJAX calls [75] and Angular Material library that provides rich and easy to use UI elements rapidly [101]. Angular is a web framework for JavaScript websites. This means that Angular is relatively inflexible, but since the frontend does not require a complex interface, it is sufficient to create the frontend for the Purrfect Cat Care System.

5.6 DNS Server

To facilitate allowing the user to easily connect to the frontend, we need to have a DNS service to let the user simple enter a normal web URL. Complex DNS servers such as Bind 9 were considered, but they are too complex for our needs.

Instead, we chose to use dnsmasq, a DNS and DHCP server intended for small networks. dnsmasq will handle creating a domain name for the frontend and each of the substations. It is easy to configure, and its low resource utilization makes it ideal for our use case. dnsmasq is commonly used in routers and internet-of-things devices for these reasons. [41]

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6 Standards

Standards are necessary for building modern systems. Without standards, it would be the responsibility of the team to create new protocols and languages just for one project, and the result would be incompatible with all other hardware and software. Sufficient standards must be chosen to allow the product to interoperate with existing systems and to lessen the burden of design on the team.

6.1 Serial Communication

The Purrfect Cat Care system has many subsystems which will need to communicate with the base station through a wireless form of communication. The base station will send the schedules for the feeding and water stations for dispensing and the amounts needed to be dispensed. The sub systems will also communicate back to the base station with their sensor readings. Within each substation, the communication between the sensor, motor, and WiFi module will be done via serial connection. These serial connections will need to follow a serial communication standard. In order to understand their impact to the project, the standards RS-(232, 422, 485), SPI, and I2C standards will be assessed.

The original serial communication standards were created for telecommunications but migrated with later versions into the realm of modern electronics. These standards defined communication between controllers and their peripherals. It is an ideal form of communication because it is simple to use. Serial connections can be simplex (one-way) or multiplex (two-way) using a half-duplex or full-duplex wire respectively. Using a full duplex means that the controller can receive information from the peripheral it is communicating with and send information simultaneously. Conversely, a half-duplex can only transfer data in one direction at a time. Serial communication can also be synchronous or asynchronous, which means that a clock would need to be accessible to both components transmitting the data, or each would need their own clocks respectively. With these basic definitions for serial communication, the standards surrounding this type of electronic communication can be discussed.

Recommended Standard (RS) 232: The RS-232 standard was created in 1960 by the Electronic Industries Association (EIA), with current versions of it still being used today, specifically for its high speed. The RS-232 serial communication standard defines communication between a Data Terminal Equipment (DTE) interface and a Data Communications Equipment (DCE) interface. A DTE can be a device such as a single board computer or microcontroller. A DCE can be a device such as a motor controller. RS-232 does not define the communication between two DCE devices, so will only be used to communicate between the main system and its peripherals attached to it. The RS-232 standard relies on a single stream of communication, meaning that a controller would need to convert any parallel communication to serial via a UART chip, which is then sent as a continuous stream of bits to the destination peripheral. RS-232 connects a single controller device (previously referred to as a master device) to single peripheral device (previously referred to as a slave device). The communication is done through a simplex setup, which requires the controller to tell the peripheral device when it is ready to receive data, and how many clock cycles it will be listening for.

Even though RS-232 holds up today, there are a few updated standards that have evolved from this original standard. RS-422 was developed by the EIA with the intention of replacing the older RS-232 standard. RS-422 boasts much higher speed, better cancellation of external signal noise, and allows for data to be sent further distances on longer cables. Like RS-232, RS-422 is a one-way simplex setup, but unlike RS-232, RS-422 can connect to multiple peripheral devices.

Another standard, RS-485 was created by the EIA in 1998 to replace the RS-422 standard. This standard boasted an improvement over each of the specs yet again, with even higher speeds, even better noise cancelling, and even longer cable lengths than before. Additionally, it allows for multiplex communication and a system of multiple controllers and multiple peripherals [112]. For consideration in the Purrfect Cat Care System, the serial communication standard candidate was the RS-485 standard due to its superior performance. However, considering all components must follow the RS-485 communication standard, and the devices may be spread out in a room, this type of wired connection may not be the best choice for ease of use of the system.

Serial Peripheral Interface (SPI): One of the two alternatives to the RS-485 standard protocol is SPI which was created by Motorola in 1979 and is not officially a standard, but is considered a "de facto" standard due to its popularity. SPI is very similar to RS-422 in that it has one controller and many peripheral devices connected together, but a very important difference is that there is only one clock which lives on the controller. The controller sends the clock signal on a separate line to all of the peripherals, making the communication synchronous, which can prevent any communication errors due to possibly mismatched baud rates. In SPI all of the peripherals are connected with just a single clock wire and a single multiplex data wire, but the data wire can be set up as a half-duplex. There is also a chip select wire for each of the peripherals so that the controller can specify which peripheral it is communicating with [81].

For the Purrfect Cat Care System, each subsystem may have one or more peripherals such as the force sensor and the motor for dispensing in the feeding and water stations as discussed in the objectives. One of the major advantages of this configuration is that the setup is cheap. There are fewer wires in a multiple peripheral setup than in the RS-422 and RS-485, there is only one clock for all of the modules, and the UART can be replaced by a simple shift register since the data is synchronous. All of these benefits also result in a system that transmits data faster and is less expensive than the older serial protocols, culminating in a stronger candidate for the Purrfect Cat Care system.

Inter-Integrated Circuit (I2C): I2C was invented in 1982 by Phillips Semiconductors, and is a different take on serial communication than the other two discussed. Whereas SPI is focused on cheap components and faster transmission speeds, I2C conserves board space and has robust error detecting built into it. I2C uses less circuit board space as it only uses two wires to connect to any number of peripherals. Unlike SPI, there is no chip select wire because each of the peripherals has its own unique address. This is because I2C transfers data via messages instead of bit by bit. Compared to SPI, I2C loses some speed since there is the overhead of sending the extra bits along with the data being sent and also requires more complex hardware components [20].

The last feature that I2C introduces is an ability called clock stretching, where depending on the device, the peripheral has the ability to pause the controller's clock, so that it could perform necessary tasks before releasing the clock to continue transmission. This is especially useful if you are using a high transfer rate and the components might need more time during certain operations, but for the rest of the time are able to operate at the higher speeds [55]. To accomplish this, it is worth noting that the clock wire for I2C is actually a full duplex, so that the pause signal can be transmitted. There is a drawback to clock stretching though, and that is if there is an error encountered due to a hardware issue, the clock can indefinitely pause transmission and halt the system. For this reason, a reset is usually built into I2C systems just in case the system locks up. For the Purrfect Cat Care system, the difference between SPI and I2C will likely boil down to speed versus cost.

6.2 Programming Languages

The Purrfect Cat Care system base station will involve the development of a "full stack," from low level device drivers to user-facing interface software. To this end, one programming language cannot satisfy all of the requirements, so multiple languages are under consideration. Programming language standards promote portability, reliability and maintainability of the programs written in these languages to be able to run on a variety of systems. Keeping these under consideration when looking at which language to incorporate in the project is important for the success of the project.

6.2.1 C and C++

The most recent published standard for C is ISO/IEC 9899:2018, also known as C17, and was published in 2018. This standard outlines the libraries available for the C language, syntax, constraints the language has, and semantic rules. Although it does not give any specific advice on how the language can be used, it does discuss what the library is designed to do given specific inputs and expected outputs.

The most recent standard for C++ is ISO/IEC 14882:2020(E), also known as C++20. This standard outlines any changes made to the language libraries. Generally, these are useful for developing compilers for the C++ language or developing new useful standard libraries which is out of the scope of this project and will not affect the Purrfect Cat Care system project. The most important thing to keep in mind regarding the standards is that the program will run on the system once compiled.

6.2.2 JavaScript

Implementations of JavaScript are based on the ECMA-262 standard, which defines ECMAScript. Currently the ECMAScript versions 1 through 6 are supported on all the modern browsers. These standards define which keywords and built-in functions are supported on browsers [**17**]. This is important to ensure the application will run on most browsers which allow for a user friendly experience when using the Purrfect Cat Care application.

6.3 Networking Standards

To satisfy the Purrfect Cat Care System objectives of being reliable and autonomous, the team considered the solutions of making the subsystems completely modular and wireless. Specifically, the subsystems would be completely self-sufficient and have no reliance on the base station for the subsystems to complete their assigned tasks, and they can be placed anywhere in the room. Each subsystem will work on its own and simply report their sensor data to the base station automatically without anyone having to hit a send button. Therefore, because the systems will not be physically connected to any other system, and they will need to communicate with the base station, a wireless communication will need to be used. This wireless communication should be easy to setup and connect to a local network. To ensure proper maintainability and modularity of the subsystems, the standards for wireless communication should be followed.

The family of standards that cover local area networks (LAN) is the IEEE 802.11 standard. The main one affecting this project under that family are for the wireless standards 802.11 which have many versions that have been updated as wireless technology continues to improve and change. These standards specify the frequency band used, data rates achievable, as well as modulation and encoding schemes among other constraints. All of these will be necessary to understand to choose the correct wireless technology that is compatible with the rest of the system and power requirements.

7 Realistic Design Constraints

Like any engineering project, the Purrfect Cat Care System is subject to certain design constraints due to some environmental factors and limiting factors placed upon the project. In the following sections, a discussion on the various constraints that limit the project will reveal several adaptations used in the development of the system as well as key considerations that should be observed in designing the subsystems. In this section an introduction of the discussion at hand highlights the key topics necessary regarding the various constraints that limit the successful completion of this project.

Economic centric constraints limit the team's ability to implement quality products with high precision and accuracy. In the case of implementing a sensor that provides slightly higher precision for twice the retail price of an equivalent model that isn't as precise but within the realm of 10%, this may be an acceptable tradeoff. In fact in all parts of the system, precision and accuracy may not be a primary focus, which may enable further savings.

In the same way that cost limits the team's ability to design, time further constricts the limits of what is possible. Some key examples may include but not limited to personnel availability, project complexity, and parts acquisition. These focuses will be discussed to reveal how the procession of time requires an adapt and overcome mentality.

Safety and health is a concern that should be paramount in the minds of any designer. In its implementation, the components should incorporate elements that maintain non-toxic materials, food grade components, and housing design that does not encourage tampering of the structure. These elements could range anywhere between the material in which the bowl is made, electronics used to provide the service should not be exposed as to promote electrical shock or biological harm to the animal, and the housing should be designed to provide a solid structural support for the on board electronics and maintain FCC standards for the food and water reservoir.

Considerations of environmental constraints limit this project in ways that reinforces the notion of being environmentally responsible. The development of the system is meant to impact the environment as little as possible. This is attained by procuring components that are economically feasible, yet provide the same quality and longevity of premium parts. The longer the product lasts the less waste that may need processing to either be recycled or sent to a landfill.

Social constraints should accommodate the usability of the product. Should this not be recognized, the success of the product may be limited. This means that while allowing for a simplistic user experience, the system should be efficient in the delivery of the information that is digestible and encourages the user to take the necessary steps that promote a healthy lifestyle for their cat. Other considerations involve the number of cats this system may service at any given time.

Finally, the importance of maintainability should be considered due to the expiration date on many products. Hardware is meant to last to a point at which it is still profitable to maintain the design. Once the intersection of quality and profitability intersect, it may not be in the interest of the designer to produce a product that is higher in quality. For this reason components should be arranged and implemented in such a way that promotes ease of replacement and affordability.

The following subsections expand on these key points given in this introduction and provide insight into the different strategies to take to accommodate the limitations that face the design of this project.

7.1 Economic

The Purrfect Cat Care System did not obtain any sponsorship, and therefore will be fully funded by the group members. According to the estimated cost of parts from the initial research, the aim was to stay under $600.00 for design parts and testing.

Due to the budget limitations, when selecting parts there may be some trade-offs between cost and precision. For example, in the initial research, there were load sensors which provided the precision needed for the Purrfect Cat Care System's feeding and water stations, however, the price of some of the parts found alone were more than half of the total budget and therefore a different solution was needed. Considering the trade-offs of cost and precision, the use of a mid-range cost and precision part could be used and supplemented with software offsets during testing. In the same way, the water pump parts initially researched for the water system were not cost effective, however the selection of two mid-range parts could be used in tandem to increase the precision to a level appropriate for the system such as a water pump supplemented with a flow sensor could be used to obtain the precision levels needed for the system. Specifically, comparing a high precision water pump with a cost of about $50 with a mid-range water pump with a cost of $12 combined with a flow sensor with a cost of $12 is about a 50% savings but can still produce a desired measurement.

In addition to the budget limitations, because the group members' focus is on the electrical components, any mechanical parts must be purchased for the project. In turn this limits the amount of the budget available for purchasing the specific design components such as the sensors, microcontrollers, and the other modules needed for the system. To lower the costs associated with some of the mechanical parts, the use of a previously owned automatic cat litter box is being used for the project. However, due to its high cost, if damaged, replacement would drive the cost up and further reduce the amount available to use toward design parts.

Finally, the goal is to keep costs down since everything would be purchased by the team members with no outside subsidies. Therefore, parts need to be selected in a way that limits the total cost of the system.

7.2 Time

As common with many projects, one of the major constraints facing the Purrfect Cat Care System is the time available to complete the design and implementation of the system. As a required capstone project for graduation consideration, this project needs to be completed before the end of the second semester of the senior design course. This imposes a hard deadline on the team to complete all of the milestones listed in this document. Within this time period the team is required to research, design, purchase parts, document the entire process and then build a prototype.

Due to the team being a larger size of five people rather than the normal four, the amount of pages required to be submitted is also greater. This requires the project to be of a larger scope and complexity to fit the five person team. However, if the project is too complex, the team risks not finishing the project in time. Due to this time constraint, the design was actually limited to exclude the original plan to have an activity station to track playing behaviors of the cat as well as provide play time automatically.

Furthermore, the procurement of parts may impose time constraints if purchased from outside of the US. To avoid this, the team is aiming to purchase the parts as soon as possible and avoid any parts that cannot be shipped within the allotted timeframe. There should be enough time to complete the prototype and begin testing on the completed system well before the end of the second semester.

Personal time constraints can also affect the total time constraints on the project. Specifically, some team members who live further away may have less time to put in work toward the project due to more time spent commuting if the team meets regularly in person. Some team members are also working while completing the project which reduces their window of availability to meet with the rest of the group. Therefore scheduling times when the whole group can meet together will be difficult. On top of these time constraints, the group members also have other courses they must dedicate some of their time to further adding to the constraints against the project.

7.3 Health and Safety

Because the system will be providing services to a live animal, there are some safety constraints needing attention. It is important that the parts that will be in contact with the cat are food grade and do not use any materials that could be poisonous or hazardous to the cat. For example the food and water bowls should be made of a material that will be resistant to bacteria and easy to clean such as ceramic or stainless steel. It is a possibility the bowls may go longer without being cleaned due to the automatic operational nature of the system. The containers for the food and water storage should also be absent of any hazardous and poisonous materials as they will hold the cat's food and water supply for seven days minimum as a specification.

Due to the electrical components and communication modules used in these systems, it is important that they follow IEEE and FCC standards. Especially those being used around the water station should be properly shielded, fully encased and not easily accessible to the cat to reduce risk of electric shock. Since cats are exploratory in nature, all moving parts should not be easy to access by a curious cat. These parts should have safety features in place that react to exogenous events. For example, the cat should not be able to get its paw inside the opening where the food dispenses as there will be moving parts. Finally, the automatic litter box should function as previously purchased. Because additional sensors, such as the humidity sensor, IR sensor and wireless communication module are going to be added to this system, they should maintain the safety level of the original product. Specifically, the IR diodes should comply with optical standards and ouput power within a safe range to avoid the risk of blinding the users of the waste station.

7.4 Environmental

The development of the Purrfect Cat Care system, has a priority to be minimally impactful on the environment. One design approach was to consider how the system was going to be powered. It was determined that wall power would be chosen for the benefit of fewer design requirements of the power system, but as a side benefit it would also help promote responsible environmental considerations by forfeiting battery usage and disposal. While portability may be convenient, it is recognized that the system does not require mobility since most of the sensors are sensitive to minute changes in its environment. Furthermore the proximity to the base station is important since the further away from the base station the weaker the signal will be to the submodules. Additionally, the quality of the sensors and motors used in the design of this product enables the system to function as long as possible before repairs or maintenance should be required. Fewer repairs means less waste produced by the product and a lower demand on the manufacturing of parts, which impacts the environment directly. Another consideration involves the incorporation of PLA 3-D printed parts. This approach, while it does use plastics, use a recyclable plastic made from cornstarch and various other biodegradable products, which will be discussed in a later section. There does require some processing to be done to reuse this material, but this type of polymer requires significantly less time to biodegrade if improperly discarded. These considerations indirectly accomplish the goal of producing a product that has a sustainable impact on the environment.

7.5 Social

The goal of the Purrfect Cat Care System is to provide cat owners a convenient and completely automatic way to track their cat's health. To do this, the system will need to interact with the cat directly. The system will automatically dispense food and water to the cat, as well as track certain statistical data from the cat's eating, drinking, and litter box habits. Some social constraints to consider for this project are related to that interaction with the system and the cat. By specification, the system is designed to handle interaction with only one cat. This constraint limits the usage of this system by those who have multiple cats. Also, the system is designed to learn the cat's behavior based on usage rather than preprogramming statistics about specific cats with certain age or health backgrounds.

Another social constraint to consider is the system should not cause the cat any harm during interaction. This includes the ability to accurately record any monitored behaviors so that the user can accurately make health determinations about their cat based on the data provided from the system. The user interface should be easy to use such that the user does not improperly use the system. Improper use of the system such as forgetting an input to the system via the application can affect its functionality and performance. This could cause it to not operate as expected and can have detrimental consequences. For example, forgetting to refill the water reservoir when alerted that it is empty could result in the cat getting dehydrated. In the same way, not filling the food dispenser could affect the cat getting fed while the user is away.

One major constraint to consider is the user friendliness of the application. The application must provide statistics of the cat's eating and drinking habits in an easy-to-understand format as well as alert the user if anything deviates greatly from the norm. The system should also alert the user when the containers for the water and feeding station are empty. This poses a constraint on the design of how often the system should alert the user without being overly intrusive.

7.6 Maintainability

As mentioned previously, a major goal of the Purrfect Cat Care system is to provide a reliable system to track a cat's health. Considering the system should run for a reasonable amount of time without needing to be replaced and can have a single module replaced, instead of replacing the whole system, is one way to reach this reliability. Therefore, there are constraints on the design of the whole system, which should follow basic wireless communication standards, as well as software standards to ensure the system can be easily maintained.

For maintainability, the parts chosen should not be of the lowest quality just to satisfy cost constraints. Therefore, there should be a balance between cost and quality for each individual part chosen for the final design in order to stay within the constraints of maintaining the system. In addition to cost and quality, the parts should also be chosen such that they are not obsolete and can be found and supported for a reasonable amount of time after the project has been completed. If certain parts used in the project become discontinued, the maintainability of the system could be affected as the module may need to be redesigned to account for the specifications of the new part.

8 System Hardware Design

The System hardware design is broken into two sections, system-level design, and module-level design. The chapter is divided into sections corresponding to each of the four subsystems. The power supply design will be discussed separately at end of the chapter due to a significant overlap of content. Within each system, various hardware modules will be introduced as well as their interaction with one another. After defining each of the relevant modules the circuit implementation for the module will be provided. This structure was chosen to provide modularity in the implementation of each module. Due to constraints such as time, cost, and especially component acquisition there will be more effective implementation of some modules.

8.1 System Block Diagram

At the top-most system level, the four subsystems will operate independently. Each subsystem will communicate with the base station through WiFi. Included in the figure below is a simple block diagram visualizing the wireless connection to the base station. The legend, and coloring, of each block indicated which person is administratively responsible for the subsystem.

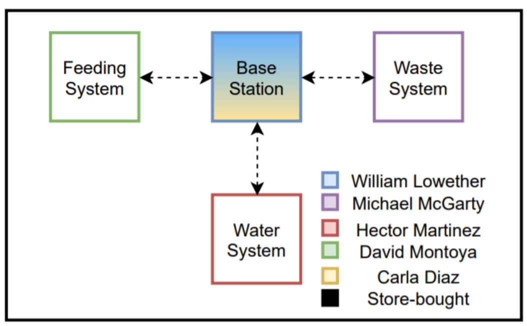

Figure 24: System overview and administrative responsibilities.

8.2 Feeding Station

8.2.1 Overview:

The feeding station is broken into three hardware sections: the dispenser, controller, and scale. The dispenser will require a motor, an attachment assembly, and a dry-food dispenser. The motor will drive either a manual feeder or a custom-designed mechanism. At the time of system design, it was unsure if the team wanted to 3D print a dispensing mechanism or purchase a ready-made dispenser. Therefore, the hardware block was abstracted to the assembly and dispenser. The scale system will require a bowl to hold the dispensed food and a weight sensor to periodically measure the weight. The hardware team was focus was on finding a cost-effective, yet accurate, weight sensor. The controller system will hold much of the firmware and controllers to activate the motor and weight sensor. The block diagram for the system is provided below.

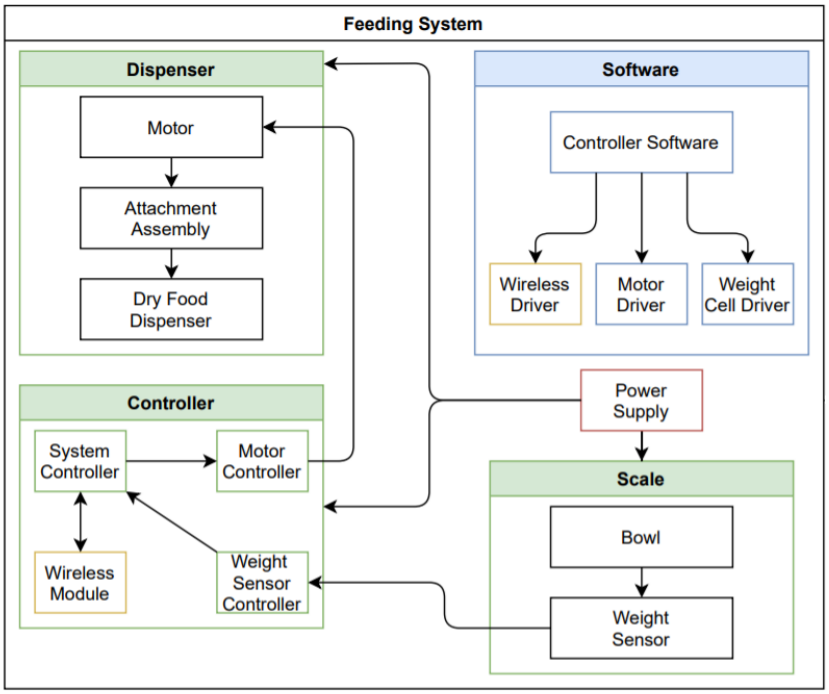

Figure 25: Feeding station block diagram

The majority of the hardware is split into the mechanics and the control circuitry. Weight sensors typically do not require complex circuitry to operate. However, stepper motors typically require some driver integrated circuit to operate effectively. Only two hardware modules are necessary, the motor and weight sensor controllers. The mechanical design and implementation will be discussed in the prototyping chapter.

8.2.2 Motor

In a previous design, the WO-417-11-18, from Lin Engineering, was initially selected to be integrated into a previous version of the Food Station. The electrical characteristics and it's integration into the DRV8428P had promising synthesis. However initial testing of the motor with a fractional load (i.e. load was less than a cup of dry food in the food hopper) in the reservoir showed promising results, it was discovered that when the load exceeded this fractional load, the food particles tend to jam the augur housing during random intervals of the rotation. It was explored that larger food particles should be used, but the same results transpired. When testing of a larger motor, 42BYGHW811 by Wantai Motor [**Proto Supplies**], with higher torque was used, this solved the issue of the jamming within the housing. The electrical characteristics of this motor has a rated voltage of 3.1 V and 2.5 A/phase. With significantly higher operating current per phase, a different driver was needed in support of its operation. Other notable characteristics that were of interest included the step precision of 1.8°. This indicates the resolution of how much food could potentially be dispensed at any given time and also determines the speed at which the rotor spins every step. As discussed earlier, the precision offered by the WO-417-11-18 may be adapted by altering the firmware in order to resolve the desired precision of the dispensed food.

8.2.3 Motor Controller

At this point the initial stepper driver required a cumbersome setup in order to operate effectively. Since replacement parts of the DRV8428P would mean down time in redesign, and initial installments proved difficult, it was decided to install the A4988 driver on top of a carrier board designed by Pololu Robotics & Electronics. It was found that the installation was seamless and required no additional adjustments other than the incorporation of a 3.3 V to 5 V inverter circuit. In this segment, the redesign choice of why the A4988 was required will be discussed followed by the electrical characteristics, design implementation of the inverter circuit, and supplementary features will be discussed.

The important features that must be met, includes the logic supply voltage range must accommodate 3 V to 5.5 V. This electrical characteristic is the min and max of the pin V_{DD} must meet should a PWM signal be used. It is important to note, that the V_{DD} on the carrier board is different from the V_{DD} on the actual chip. Pin 7 on the carrier board correlates to the V_{DD} on the A4988 chip, while pin 2 is V_{DD} shown in Figure 26. The PWM signal coming from the microcontroller will send an oscillating wave of 3.3 V as the low logic and 0 V as the high logic to the STEP pin of the driver carrier board. This input may be realized by using an inverter circuit, Figure 27, where a 5 V plane reads across the junction of the MOSFET and R_1 when the MOSFET is off and 3 V when the MOSFET is on. Given the characteristics of the chosen motor, the step precision of 1.8° was sufficient enough for resolution required, hence the microstepping pins MS1, MS2, and MS3 were all tied to ground to indicate default setting of full step resolution and two phase excitation mode. Features of the sleep pin, enable pin, and direction pin were all connected to the microcontroller to offer control over these domains should the need arise during the firmware design.

Since the use of the A4988 on top of the manufactured carrier board, design of the circuit that controls the current $I_{TripMAX}$ was not considered. This eliminated the need to consider how the circuitry for the internal PWM current control had to be developed as well as current decay mode considerations. Control of the ENABLE input had been tied to the output of the microcontroller in order to maintain full control of whether or not the FET outputs could be turned on or off. When ENABLE is set high, the FET outputs are disabled. The SLEEP pin is also tied to the microcontroller in order to put the internal circuitry into a low powered state.

During normal operation the pin being tied high offers normal operation.

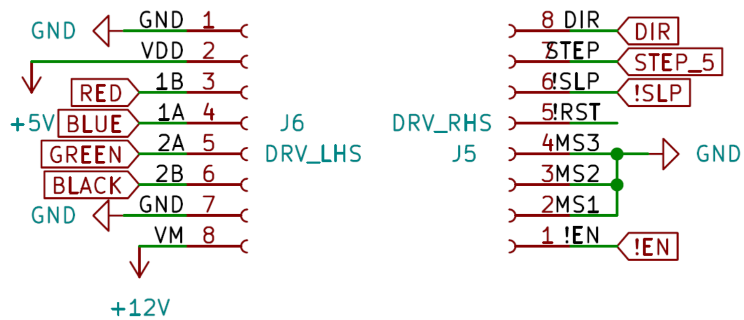

Figure 26: Stepper driver carrier board schematic.

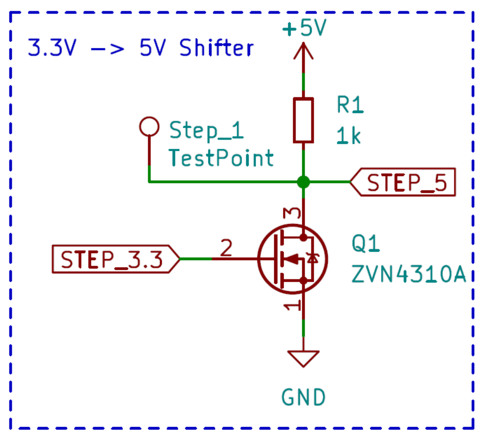

Figure 27: 3.3V to 5V inverter schematic.

8.2.4 Weight Sensor Controller

The ADS1231 from Texas Instruments forms the heart of the load cell controller. Calling the IC a controller is a bit of an over-simplification since the device is an amplifier and ADC in one package. Regardless of the analog and digital nature the implementation is quite simple and only requires a few components. Note that the logical pin locations are different from those in the datasheet and both the KiCad footprint and symbol are available on the device's product page.

Before discussing the component choice it is important to discuss some of the pin functionalities to better understand the reasoning behind the schematic, Figure 28. The AVDD and DVDD pins correspond to analog and digital respectively. The AINP and AINN pins represent the analog input voltage for the positive and negative of the bridge. Positive and negative are somewhat ambiguous in this connotation, however, they represent the connection between the two load cell sense lines. The VREFP and VREFN pins provide a differential reference voltage to the ADC while the device is turned on. Ideally, the reference should be identical to the excitation voltage to best give a full-scale reading. The capacitor pins require an external 0.1 μF, c0g, capacitor to be present. The external capacitor is necessary to establish a low-pass filter with a cutoff of 720 Hz. According to the datasheet, the filter reduces aliasing effects on the ADC and reduces high-frequency noise content from the measurement.

The switch pin serves as an optional grounding switch. The load cell's ground could be connected directly to ground or to the switch pin. If tied to circuit ground a small current always passes through the device. The input current to the load cell is small, approximately 5 mA for a cell with an excitation of 5 V and an input resistance of 1 kΩ. The resultant current is somewhat small but not negligible. To reduce the wasted power, the load cell ground is connected to the switch pin. The switch pin connects and disconnects the load cell's ground terminal from ground automatically. The switching is done in response to a request from serial data on the SCLK and DOUT pins. These two pins form a standard SPI interface. The PWDN pin is short for power down. By pulling this active low pin low the entire chip is powered down, reducing total power draw. The line can be pulled back high to turn the chip back on.

The last two pins, SPEED, and CLKIN are related. The CLKIN pin allows an external clock to be used. The datasheet recommends providing either a 4.9152 MHz clock to this pin or tieing it low to take advantage of the internal oscillator. The frequency of the internal oscillator is ambiguous, however, it is likely below 200 kHz. Internal circuitry switches the internal oscillator off for signals above 200 kHz on CLKIN. The lack of internal oscillator frequency is insignificant as the SPEED pin controls the sampling rate. When pulled high, 80 samples per second (SPS) is output and 10 SPS is output when tied low. Not much is to be said about the ground pins, they represent ground for both the digital and analog supplies.

The schematic for the load cell amplifier implementation is provided below:

On the top-left corner of the figure lies a 3.3V rail powering both the analog and digital supply pins. It was assumed valid to tie the two pins together for three reasons: 1. The datasheet mentions several times the parameter AVDD = DVDD, 2. The ground is stated to be shared by both analog and digital supplies, and 3. any inaccuracies in the output measurement will likely be predictable if this is an issue. The primary reasoning is if the analog and digital supplies explicitly needed to be isolated then it would be mentioned in the design sections. Similarly, a stable digital supply can be generated by placing several bypass capacitors across the supply pins. The capacitors C5 and C6 correspond to these bypass capacitors. The datasheet recommends a minimum of 0.1 μF to smooth the supplies. The use of a 10 and 1 μF capacitor will be more than sufficient in stabilizing the supplies.

The excitation voltage and ground pins from the load cell are tied directly to the VREFP and VREFN. Connecting the excitation to the reference will hopefully eliminate any instability in the excitation voltage on the sampling. As mentioned the SW flag is only to keep the schematic as readable as possible. The PWDN, SCLK, and DOUT pins are all connected to global nets

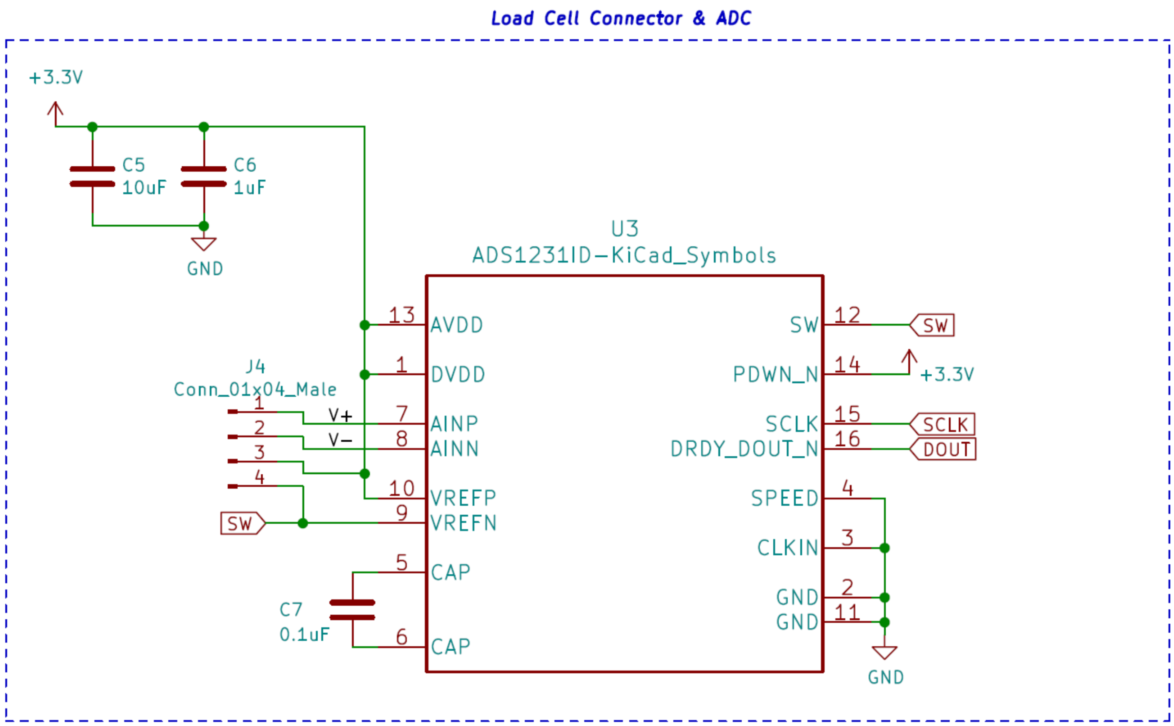

Figure 28: Load cell amplifier.

that connect to the GPIO and SPI pins, respectively. Lastly, the speed pin, clock pin and ground pins were all tied to the ground. The choice to tie SPEED and CLK to ground was made predominantly in that adjustment of this pin through the GPIO was not needed and applying an external clock is unnecessary. Oversampling the ADC does not seem necessary nor appropriate since samples will be taken every several minutes. Reasons for these optimization choices will be discussed on page 151.

8.2.5 ESP Integration

The last hardware component is the interface between the ESP and the surrounding circuitry. An ESP development board has been chosen to minimize the resources needed to develop our own development board. The board has two rows of 15 headers pins which connect to core modules such as the ADC, GPIO, serial interfaces, and much more. The following figure describes how the various flags in the motor and load cell controllers interface with the ESP. The only notable connection is the STEP3.3 pin since it requires a PWM capable pin. The SCLK and DOUT pins correspond to the SPI interface, and the remaining connections, excluding +5 V, correspond to GPIO pins. The development board can be powered by an external 5V rail connected to pin 16. Two small bypass capacitor is placed across the ground and 5 V lines to minimize the ripple. The values of 1 to 10 μF capacitor should be more than sufficient.

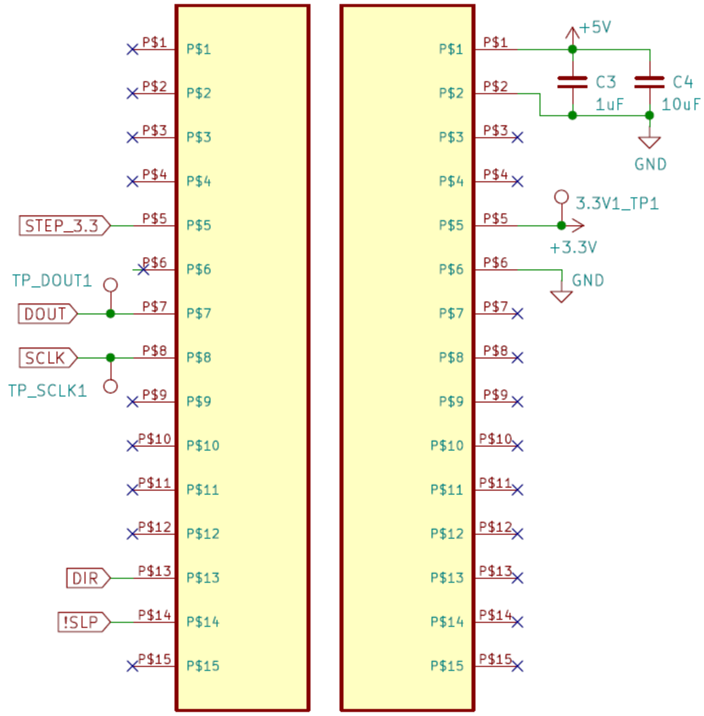

Figure 29: ESP breakout header schematic.

8.3 Water Station

8.3.1 Background

The following sections provide a brief description on why the regulation of water is so important to animals, especially cats. The statistics provided will help motivate why an automatic water bowl will not only benefit the cat's health but also the encourage a positive association with the water bowl.

Dehydration in cats is a frequent consequence of chronic kidney disease (CKD), and it can culminate in low appetite , drowsiness, weakness, constipation, and an increased vulnerability to uremic crisis. It may also trigger pathophysiology reactions that are hazardous to the kidneys. [39] While dehydration is a frequent cause of CKD, overhydration can be just as dangerous. As the kidneys deteriorate, their capacity to eliminate water from the body is impaired, making overhydration a danger that can have harmful repercussions. Excessive hydration can cause visible symptoms such as third-spacing and can be harmful to the renal parenchyma. [39]

A recent study found that cats fed a wet food containing 70% moisture had lower urine specific gravity, less weight gain, and greater physical activity than cats fed a dry diet containing 10 moisture. Furthermore, research examining water balance in cats found that cats fed canned food had considerably higher water consumption per gram of dry matter than cats fed dry food.[80] Many cat owners would rather assume their cat is drinking enough than to know how much they drink. While 79% of cat owners feel their cats drink enough water each day, just 37% realize how much water their cats need to consume daily. [39]

8.3.2 Overview:

The water system functions very similar to the feeding station. The system currently relies on one of two measurements to determine water intake, weight and volume. Ideally, a water flow sensor and load cell would be used in tandem to measure both the weight of dispensed water the the rate the water flows into the bowl. This redundancy is needed to ensure the proper quantity of water is dispensed. Using purely the load cell would introduce a delay, potentially resulting in more water being dispensed. Throughout development it was deemed that the flow sensor was not an integral component. The flow rate of the purchased pump is on the order of 100 mL per minute. The delay introduced by the microcontroller and other processing is negligible due to the long dispensing duration. For context, the team thought it would be an interesting challenge to try and make the dispensing as accurate as possible and integrating the flow sensor with pump will minimize this delay. If a greater flow rate pump were used the flow sensor becomes more of a necessity.

In addition to the challenge, there are benefits to keeping small volumes of water within the bowl. One member of the team has a cat which does not like being unable to see the bottom of the bowl. The cat will swat water out of the bowl before drinking. Issues such as still water, food crumbs, and being unable to see the bottom of the bowl only deter the cat from drinking more often. Hence, the load cell will be present to verify the volume remains at a threshold such that the cat does not become frustrated. Leading to less messes, a generally cleaner bowl, and a happier pet. To reiterate, the load cell is needed to track long-term water changes but is also fast enough to provide rapid measurements with sufficient accuracy.

The hardware breakdown for the water system is less mechanically involved than the food station. The pump is the main mechanical component, but additional components such as the reservoir and food bowl will add to the design complexity. It was decided early on to 3D print the reservoir and pump. The benefits to 3D printing these parts will be discussed in the prototyping section. However, the short reasoning is for prototyping flexibility. By 3D printing the bowl and reservoir the team had greater freedom with how the parts will integrate into a full system. The flow sensor, weight controller, and load cell controller form the bulk of the electrical design. The purchased pump has a relatively low flow rate and component testing yielded the flow rate is dependent on voltage. As mentioned, the low flow rate removed the need for the slow sensor, however, it is still included in the high-level block diagrams. The block diagram for the water station is provided below.

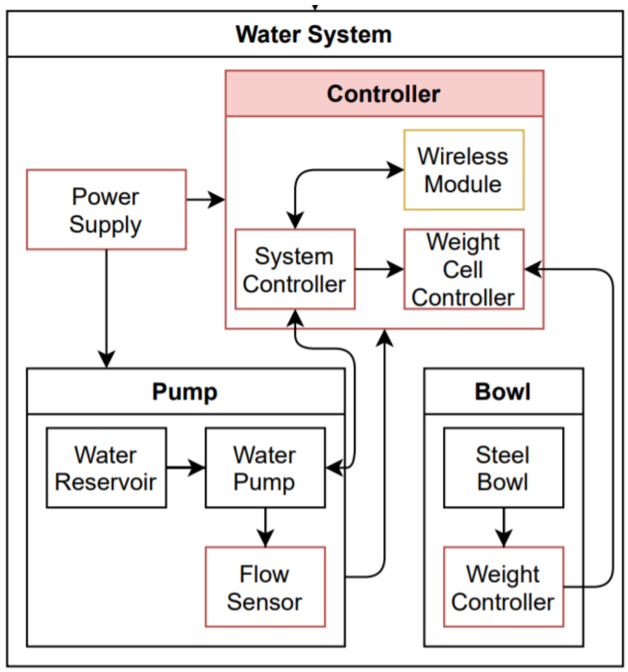

Figure 30: Water station block diagram

8.3.3 Pump Controller:

The pump controller, in the following figure, is designed to quickly, and safely, turn the pump on and off. One of the microcontroller's GPIO pin connects to the diode's anode of an optocoupler. The optocoupler isolates the pump circuitry which operates at 12 V and with a typical current draw of 250 mA. In the instance of a power surge or some unknown edge case the optocoupler will prevent a surge from injecting this large from the pump circuitry to the ESP. The ESP has a relatively low current draw of 10 mA on any pin, hence the protection circuitry was necessary.

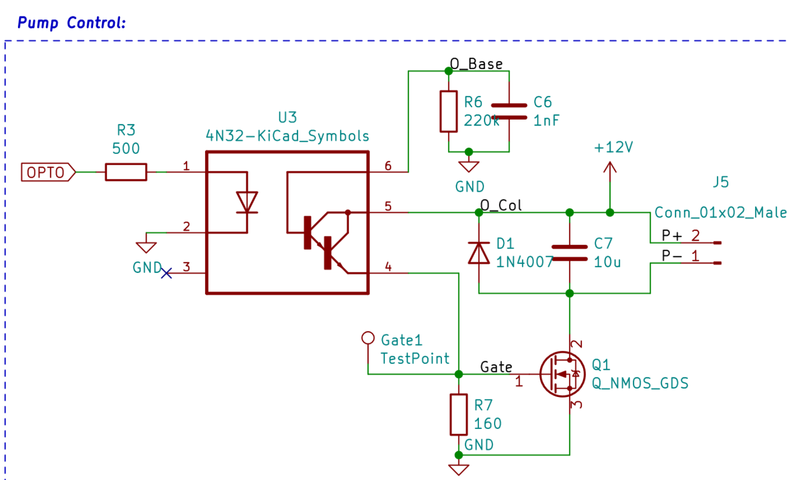

Figure 31: ESP-Pump Controller interface.

On the input of the optocoupler the 500 Ω resistor that limits the current through the input diode. The diode has a forward voltage of approximately 0.7 V when operating at a few milliamps. The large current gain forced the input current to be set at approximately 2.5 mA. The ESP has a logic high value of 3.3 V, implying the drop across both the resistor and diode results in approximately 3 mA through the diode. With a current amplification of approximately 10, 30 mA is seen at the output of the optocoupler, which provides sufficient drop across R6 turning the MOSFET on; $V_{GS} \approx 5$ V.

The pump is a DC pump that will only operate when a 5-15 V voltage is applied across the terminals. The applied voltage results in a current which flow across the plates of the commutator and in turn drives the rotation of the rotor. To switch the voltage across the pump in a controlled manner an n-channel MOSFET is placed in series with the pump. The pump is attached from the the drain of MOSFET to 12 V through the connector with terminals P+ and P-. Placing the pump in series with the MOSFET's drain guarantees that the voltage applied to the gate directly contributes to the gate-source voltage of the MOSFET. The gate biasing is controlled indirectly by the ESP through the use of an optocoupler. A Darlington output optocoupler was chosen to provide a significant current gain which ensure a large V_{GS} is achieved. The gate-source resistor converts the output current from the optocoupler into the gate-source voltage. The value for the resistor is heavily dependent on the source current since the chosen optocoupler has a gain of up to 13 times when run from a 12 V supply. Also, the CTR for the optocoupler is dependent on the collector-emitter voltage of the optocoupler's Darlington output. The assumptions in the prior paragraph are valid since a collector-emitter voltage of 7 V still provides suitable amplification of the current.

The chosen optocoupler has an open-base allowing for an RC network to be attached. The capacitor allows the base to hold a constant voltage while the internal diode is activated. Once the GPIO is pulled low and the diode turns off the parallel resistor will allow the stored charge to slowly dissipate. A capacitance of 1 nF is sufficient for the 1-2 V on the base and the 220 kΩ capacitor gives a time constant of 0.22 ms. Implying that after 1 ms the capacitor will be essentially discharged. The last components are the diode and capacitor across the pump terminals. The capacitor is necessary to remove unwanted voltage spikes across the pump. An experiment was done running the pump from a 12 V DC supply and voltage spikes on the order of $\pm 30V$ were present. Once a 10 μF capacitor was introduce the spikes were immediately suppressed. Similarly, when the pump turns off the current through the internal inductor forms a back-emf across the terminals. Placing the diode, or varistor, suppressed the back-emf keeping the surrounding circuitry safe. A 1N4007 diode was used as a flyback diode due to the back-emf being relatively insignificant. Other diodes are suitable, such as a standard 1N4148, however the 1N4007 was chosen due to the 250 mA current draw from the pump.

8.3.4 Level Sensor:

The level sensor is arguable the simplest circuit of the station. The sensor requires GND to be spread across two pins. A digital output voltage is present from 0 to 5V with the high and low states representing full and empty respectively. Full and empty are ambiguous but the sensor is only able to detect is water is above or below it, implying the reservoir will be full or empty depending on where it is placed. The datasheet for the device required a 4.7 kΩ pull-down resistor on the output pin. Similarly, a 390 Ω resistor is placed in series with the output signal pin. The necessity of the series resistor is unsure but it is recommended by the manufacturer without much reasoning. The LSOUT net connects to a voltage divider near the ESP to guarantee voltages above 3.3 V will not reach the ESP. Two 100 kΩ resistors were used to form a divider with relatively high impedance and which would not load the 4.7 kΩ pull-down resistor. The team was unable to find the input impedance for this ADC pin but testing confirmed the resistor choice was sufficient and no loading occurred.

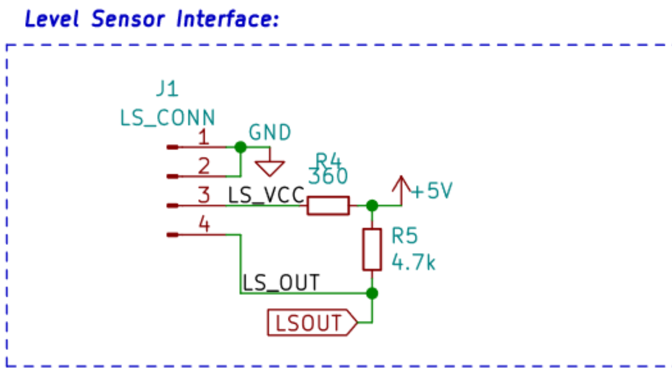

Figure 32: ESP-Level Sensor Interface

8.3.5 Weight Sensor Controller

Refer to the load cell implementation on page 91. The implementation will be identical including component choice and interfacing with the ESP.

8.3.6 ESP Integration

Similar the the food station, the ESP will interface with the surrounding circuitry through external header pins. The interface with the load cell is connected using the same pins. Another SPI interface is available if a flow sensor were to be used, only requiring the nets be connected on the schematic. The same 1 μF capacitor is placed across the power rails. Lastly, the voltage divider from the level sensor is shown in the top-left corner of the schematic. The divider may be replaced with an op-amp based attenuator if the additional resistance causes issues with the output signal. A capacitor is placed in parallel with the ADC pin to remove any high frequency noise on the digital output of the level sensor. The level sensor will be a non-negligible distance from the remaining circuitry implying the signal will need cleaning before reaching the ESP's built-in ADC. The interface with the ESP is provided in the figure below.

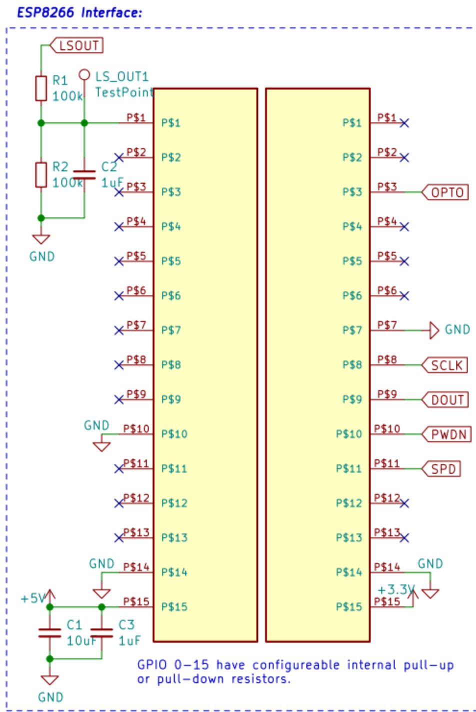

Figure 33: ESP Header Pin interface and connections.

8.4 Waste Station

8.4.1 Overview

While arguably another mechanics-heavy system, the waste station has been designed to be the simplest station of the project. Implementing the mechanism from scratch would have placed this project beyond the scope of a senior design project. The additional time, resources, research, and development would have provided a marginally better product in the end. Initially, a group member who owns an automatic pet feeder would have been used as the base and data collection modules would be appended to it. However, throughout the design it seemed more reasonable to append the circuitry to a traditional litter box. Internal conversations motivated this choice since a traditional litter box is available at most big-box stores, and it would be surprising if the majority of pet owners own an automated litter box over a traditional box. In addition, the traditional litter box eliminated transportation issues and the risk of damaging a team member's personal property.

The core additions to the waste system will be a proximity sensor used to detect if the cat has entered the litter box and the humidity sensor to detect urine or excrement. Additional electronics are necessary to properly drive, receive data from, and transmit data back to the base station. Upon detection, a counter is updated within the system controller and a humidity sensor is activated. The humidity sensor will sample for several minutes and attempt to detect an increase in humidity. If a cat is urinating it is expected that the relative humidity increase by several percent. If the cat is defecating, the humidity will likely increase due to the cat breathing, however, it should not be to the same scale. The overall system block diagram is provided in the figure below.

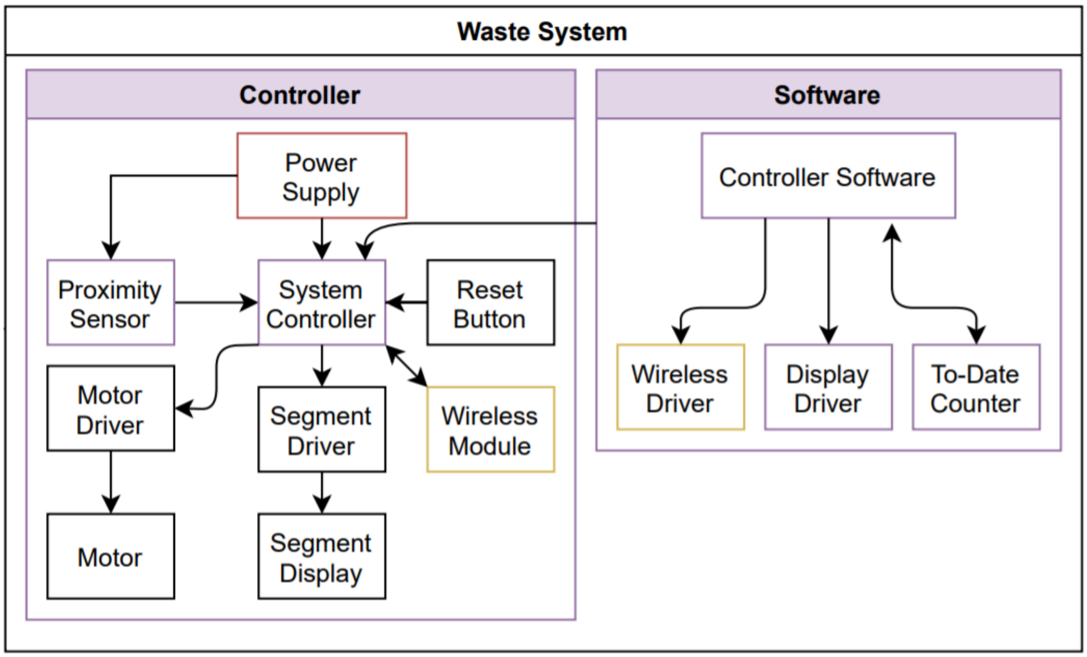

Figure 34: Waste station block diagram

The figure above includes several blocks not implemented in the final design, but would be included given additional time. The motor driver and motor blocks are not relevant as it included to model a system made from scratch. Throughout the team's technological investigation, many of the automated litter boxes feature a seven-segment display showing the total number of uses and a reset button to reset the count. The final waste station implementation does not include the display and reset button. Instead, this information is sent to the user's dashboard where they can view the total count there. Again, given additional time implementing the hardware would provide a convenience factor for the user as they do not need to access the website and can simply glance over at the station.

8.4.2 Signal Generation

The trusty LM555 timer forms the heart of the waste stations signal generation. The square wave generated from this circuit will modulate a hypothetical bit stream across the IR transciever. A hypothetical bit stream is used since no data is being modulated, it is the carrier itself being sent and detected by the transciever. The oscillation frequency was set to 38 kHz since the purchased

IR transciever, and many others, operate best under 38 kHz modulation schemes. The schematic below provides the final implementation of the clock generator.

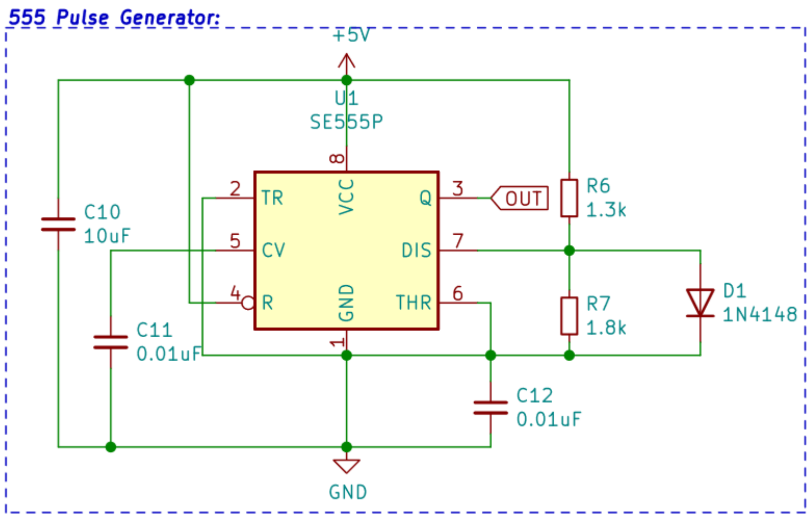

Figure 35: 555-timer 38 kHz astable oscillator implementation

The 555 will operate from a 5V supply, with a 10 μF capacitor acting as a bypass capacitor. The 0.01 μF capacitor on the control pin is a standard value provided in the data sheet. The connection will not be discussed in detail since the astable oscillator configuration is discussed heavily in the data sheet and the only difference is the bypass diode across R_7. To set the output to a square wave a diode is necessary to bypass R_7 on the charging cycle. Without the diode another configuration, or topology, would be needed to generate the square wave. Ideally the two resistors R_6 and R_7 would be identical. However, the forward voltage of the diode affects the time constant for the charge and discharge cycle. Ignoring the drop of the diode, and using sample component values of R_6 = R_7 = 1.3 kΩ and C = 0.01 μF the theoretical frequency is 32 kHz. The frequency was calculated from the following equation in the datasheet.

$$f = \frac{1.44}{(R_A + 2R_B)C} \tag{1}$$

The above equation is helpful in determining approximate component values near 38 kHz. The resistors were then tuned empirically to cancel the discrepancy in time constants due to the diode forward voltage. The final values of 1.3 kΩ and 1.8 kΩ resulted in a near accurate 38 kHz. The theory is that reducing R_6 reduces the charging time constant and subsequently the total time spent charging C_{12}. Inversely increasing R_7 increases the discharge time constant and subsequently the total time C_{12} discharges. Without the diode the charging time constant is large, due to both R_6 and R_7 charging the capacitor. Hence, it seemed likely that decreasing R_6 would help equalize the two time constants. Any change made to R_6 was made opposite to R_7 to keep the total resistance of R_6 and R_7 fixed. It was unsure if this condition was necessary but increasing the discharge time as well would only make the tuning process easier.

8.4.3 Proximity Sensor

The hardware for the proximity sensor is quite minimal. The output from the 555 is fed through a 370 Ω series resistor to limit the current through the IR transmitter. Testing was done to choose an operation point such that the receiver could detect from 1 meter away. Initially, a 10 mA current through the diode seemed like a reasonable starting point. From the data sheet, 10 mA through the diode results in an output intensity of 4 $\frac{\text{mW}}{\text{sr}}$. This intensity should be sufficient in being detected since the detector can detect quite low irradiance at an advertised distance of two meters.

The forward voltage at 10 mA is approximately 1.2 V. Hence, the 370 Ohm resistor limits the current to approximately 10 mA since the drop across it is approximately 4.1 V. The detector does not require additional circuitry, only a power connection to 3.3 V. The output bit train is provided on the signal pin which connects to the microcontroller. Throughout testing, this initial configuration of a near 10 mA diode current provided successful detection over one meter. For future works, decreasing the current through this diode to generate a radiant intensity more appropriate to the 1-2 foot distance could decrease the overall power waste of the system. Also, it is important to note the crossing of voltage domains. The transmitter operates in the 5 V domain since the ESP is independent of the square wave generation and transmission. Operating the receiver at 3.3 V is fine since the optical beam is present as long as the diode is properly biased. The receivers interface with the ESP forces it to be on the 3.3 V domain which is within the devices specification.

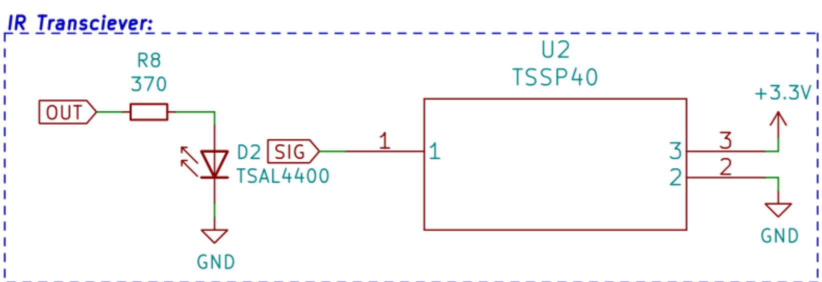

Figure 36: IR transciever schematic.

8.4.4 ESP Integration

As with prior stations the ESP integration is fairly minimal. The same 5 V rail with a 1 μF capacitor is used to power the ESP. The signal from the receiver is attached to a GPIO pin. Throughout testing, the receiver behaves slightly different as initially expected. It was thought that the bit stream would be present on the output pin of the receiver. However, when a bit steam was present the output pin was pulled high. Inversely, if the stream was not present then the pin was pulled low. These observations greatly simplified the interface with the ESP as a GPIO could be assigned an interrupt which triggers every time the pin toggles from high to low.

The interface for the humidity sensor is also present. As mentioned in Chapter 4, the humidity sensor utilizes an I^{2}C interface, and the manufacturer recommended two 10 kΩ pull-up resistors on the clock and data lines. The ESP interface implementation is quite simple, and provided below.

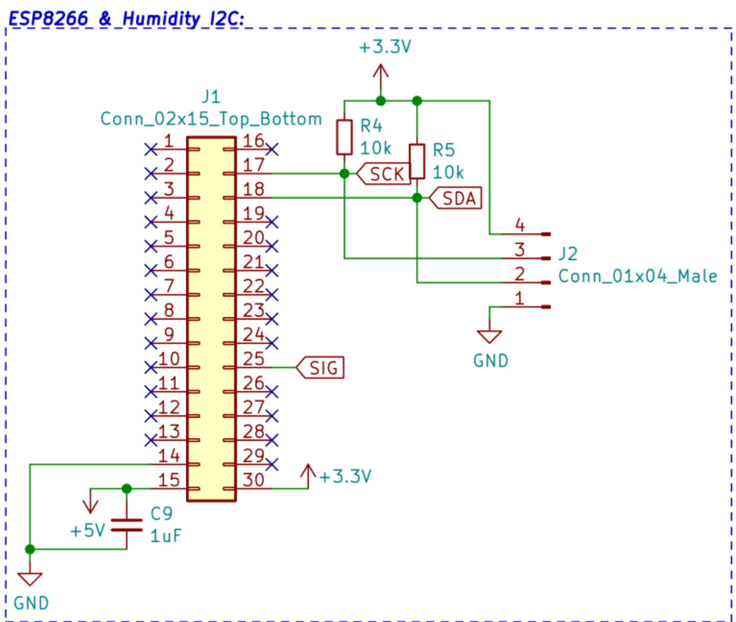

Figure 37: Waste station ESP interface.

8.5 Base Station

From a hardware perspective the base station does not require any design. A Raspberry Pi model 3 has been purchased to host the user interface, server implementation, and such. Being the most free-form of all the modules, the station could easily be replaced with other development boards for those attempting to recreate this project, but there exists zero hardware contribution.

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8.6 Power System

To power the various subsystems involved within a single PCB module, the circuit requires conversion down from a 240 VAC wall line to a set of regulated DC voltage rails. Initial voltage distributions were to be mirrored for the food and water station in order to enable uniform design. For the water station it was decided that 12 VDC would power the pump and output side of the optocoupler, 5 VDC would power both the level sensor and ESP8266, and 3.3 VDC would power the ADS1231 and the load cell. Luckily, the chosen ESP development board supports a 5V input with a built-in regulator dropping the 5 V line to 3.3 V. Therefore, the 3.3 V does not need to be externally generated.

Each of the core modules in the water station were tested. The optocoupler driver was the initial focus of these tests since it was at first the only component to cross voltage domains; 3.3 V and 12 V. The first design involved driving the optocoupler with 5V at the collector. The 5 V is sufficient but the current gain is greatly reduced. Recall that the collector-emitter voltage creates a family of CTR curves. When the optocoupler is activated the voltage at the gate is non-zero, implying the CTR decreases with the Darlington's output current. Utilizing a 12V collector voltage drastically increases the current gain across the optocoupler, relaxing the constraint on the ESP side. Other optocoupler types were investigated and tested but the devices focused on isolation as opposed to current gain. The maximum output current of an ESP GPIO pin is 10 mA and assuming an ideal optocoupler would require large resistance to adequately bias the gate. With the larger current gain, a smaller resistor can be used at the optocoupler's emitter to lower the output resistance seen by emitter. The design revision is mentioned because it directly impacts the power supply design. The system requires a 12V rail to power the pump and the collector of optocoupler.

The food station also requires a 12 V rail. The documentation and experiments with the Hybrid Stepper motor from Lin Engineering proved that it could provide significant torque from a 12 V rail. Although the motor was not used in the final design, it forced future motor drivers and motors to support a 12 V rail. In addition, the documentation from Lin engineering did not seem to imply that a higher voltage would provide more torque. The quantity of interest was the current through each phase of the motor. Therefore, leaving the supply voltage at 12 V was not a substantial tradeoff.

In order to achieve this setup, the design requires the use of a voltage step-down regulator, or more simply a Buck converter. A 12 VDC wall plug was purchased to provide 12 VDC. It was decided early on that designing the power supply from scratch, albeit interesting, was not within the scope of what the team wanted to achieve with this project. Using a larger power wall plug is an option but adding an additional regulation stage adds unnecessary complexity. The design of the power converter was taken from Texas Instrument's (TI) WEBENCH® Power Designer. Several designs were considered but the key choice driving the decision was part availability.

At the time of writing this, the supply of switch-mode regulators is still incredibly thin. Throughout the design process, it was paramount to find a regulator that at least met our specs. This part shortage is mentioned because the power supply design overachieves the modest power requirements of each system and finding a design which met more lofty specifications was overlooked for part availability. The chosen buck converter requires a nominal input of 12V and a produces voltage output of 5V. The maximum output current was set to 1.5 A, a 3X overestimate of the theoretical maximum current draw for any station. A 10% input voltage ripple was assumed, albeit slightly overkill for most DC wall supplies. A brief search of wall plugs presented typical values of a 5% load regulation for a variety of different wall plugs. These design specifications produced many different buck converter designs. The chosen design exhibits a 94% efficiency when operated at the expected 1.5 A output. The report for the converter does state that the efficiency will drop off substantially if the current draw is below 100 mA.

The aforementioned topology for the water system required a buck converter for the purpose of stepping down a voltage of 12V to 5V. The current system has no need for regulation at other voltages higher than the input voltage, which is what a boost converter would accomplish. An honorable mention to the buck converter, might be a buck-boost converter since the circuitry enables the flexibility of increasing the voltage regulation or decreasing the voltage regulation depending on the application [45, 47]. As the name implies, the topology achieves these characteristics by placing the inductor at the input of the circuit and diode at a junction that is connected to a switch. This configuration produces a negative voltage with respect to the input. In a technical blog by Mouser Electronics, this characteristic may complicate certain designs and are generally used for high powered LEDs. An additional downside to this topology requires the design to include components that promote the characteristics of both a boost and buck converters, which requires a larger footprint. Often times these topologies will require higher quality and higher rated elements to handle the demand of higher input voltages and currents.

In the next sections, the power requirements, supply design, and component choice will be discussed..

8.6.1 Food Station:

Partially due to the lack of low-current switching regulators a high-current regulator was chosen to accomodate the food station power requirements. The power breakdown is provided in the table below.

Summing the current for each rail, approximately 600 mA will be supplied from the 12 V rail, 400 mA from the 5 V rail, and 15 mA from the 3.3 V rail. With the stability of the supply current being unknown tripling the value was recommended by our advisor, Dr. Chan. The net power the supply will need to provide is approximately 9.25 W.

The 3A maximum output TPS54328D regulator from Texas Instruments® will be sufficient meeting the increased power requirements of the stepper motor [145]. Hence, the reference design provided in the water station section will be reused for the food station design.

Component	Max. Current (mA)	Approximate Max. Current (mA)	Voltage Rail (V)
ESP8266	170	400	5
TAL220 (Load Cell)	5	N/A	3.3
ADS1231 (ADC)	10	N/A	3.3
WO-417-11-18	600	N/A	12

Table 6: Food Station Power Table.

8.6.2 Water Station:

The power breakdown for the water station is very similar to the food station. More components are required with the water station but the net current draw is still less than that of the food station. The power table is provided below.

Component	Max. Current (mA)	Approximate Max. Current (mA)	Voltage Rail (V)
ESP8266	170	400	5
TAL220 (Load Cell)	5	N/A	3.3
ADS1231 (ADC)	10	N/A	3.3
FS-IR02 (Level Sensor)	12	25	5
Peristaltic Pump	250	N/A	12
Pump Control	N/A	50	12

Table 7: Water Station Power Table

The current draw for the level sensor was nearly doubled because the average operating current was given. Experimentally the peristaltic pump was found to draw 250 mA. Lastly, the pump control was approximately to 50 mA due to the large current gain on the output of the optocoupler. Designing the supply with some headroom will allow us to optimize the power draw from the ESP GPIO. Therefore, the net power for the water station is approximately 7.3 W

The reference design provided by WeBench®, preferred components, and the final schematic is provided below. Note the waste station power requirements were not addresses before finalizing the power supply design because the net power usage is much below that of the other stations. Approximately speaking, the ESP is the predominant component which consumes 2 W at worst.

The above requirements are also satisfied with the TPS54328 4.5-V to 18-V Input, 3-A Synchronous Step-Down Converter. The adaptive on-time control allows for a smooth transition from PWM mode , under greater load, to Eco-mode operation at low loads. Using Eco-mode, the TPS54328 can sustain excellent efficiency even under light load situations. The TPS54328 also contains a unique circuit that allows it to use low equivalent series resistance (ESR) output

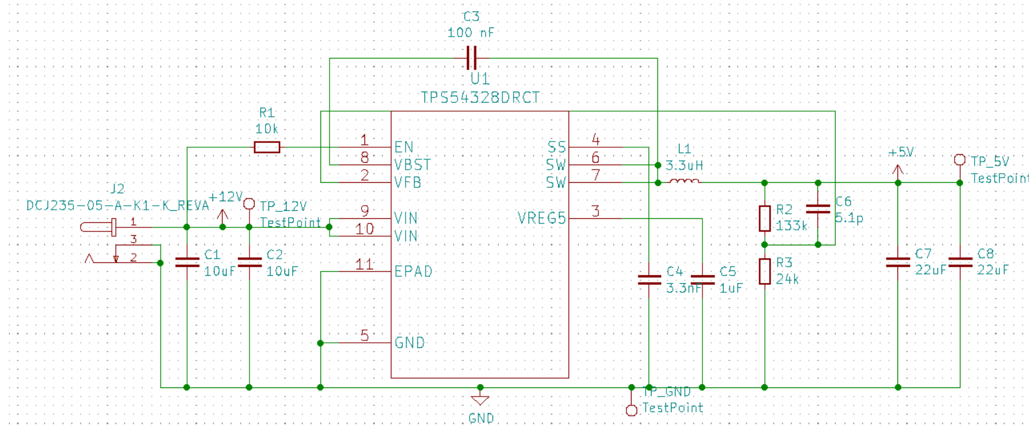

Figure 38: Reference Water Power Supply design.

capacitors such as POSCAP or SP-CAP as well as ultra-low ESR ceramic capacitors. The device accepts input voltages ranging from 4.5 to 18 volts. The output voltage may be set between 0.76 V and 7 V. The gadget also has a gentle start timer that may be adjusted. The TPS54328 is available in 8-pin DDA and 10-pin DRC packages and is meant to function in the –40°C to 85°C temperature range.

Unlike other schematics, much of the design has been provided by WeBench. However, a brief high-level overview of the component and their purpose will be included. Starting from the left-most end of the figure above, a DC wall jack interfaces with 12 V wall plug and the input pin of the chip. The 10-pin variant will be used in the final implementation, which interestingly has two input voltage pins. The two capacitors C1 and C2 are low ESR input bypass capacitors. The design file recommends 1 mΩ ESR ceramic capacitors to minimize heat due to input ripple. The R1 resistor is used to tie the enable pin high. The chip allows for digital control of the converter but the functionality is not necessary for our purposes. The EPAD and GND pins correspond to power and signal ground respectively, and are shorted together. The bootstrap capacitor is needed to aid with the switching of the high n-channel MOSFET driving the output. A relatively small value of 100 nF was recommended. The last pin on the left side of the ship is the feedback pin which connects to a resistor divider at the output terminal. The divided value is partially filtered by the capacitor on the top-leg of the divider but will not affect the DC value. The feedback is necessary to maintain a stable 5V output.

The inductor is a standard fixed 3.3 μH inductor. The design recommends a low DC resistance of approximately 30 mΩ for the inductor. The low value is needed to minimize series losses cause by the output voltage ripple. Typically the low DC resistance is not an issue for an inductance on the order of several μH. A capacitor is attached to the SS pin, short for soft start control. The capacitor helps with suppressing transients associated with suddenly applying power to the circuit. The VREG5 pin is just a 5.5 V output pin with a capacitor holding the voltage constant. It is interesting to see the fixed 5.5 V output as a convenient way to power TTL logic without the need for the core switch-mode implementation. Lastly, the two output capacitors are used to significantly increase the output capacitance. As with all the other capacitors, low ESR is preferred to minimize losses. However, the design relaxes the ESR on the output capacitors to approximately 3.7 mΩ. The larger ESR is likely due to a 22μF capacitor innately having a larger ESR than a 10 or 0.1 μF capacitor. The design also provides additional properties each component should have, however, this is more of a concern for the prototyping of the circuit and will be discussed later.

As for some of the qualitative properties, the TPS54328 has an Auto-Skip Eco-Mode to improve light load efficiency. As the output current reduces due to the high load condition, the inductor current drops, until the rippling valley hits zero; the border between continuous and discontinuous conduction modes. When the rectifying MOSFET detects zero inductor current, it is shut off. As the load current declines more, the converter enters discontinuous conduction mode. The on-time is about the same as it was in continuous conduction mode, hence it takes longer to discharge the output capacitor with a lower load current to the reference voltage level.

The gentle start function may be adjusted. When the EN pin becomes high, a 2-μA current flows through the capacitor, which is linked from the SS pin to GND. During startup, the output voltage is kept under tight control. The datasheet provides equations for the light load current and the start time, however, it is not planned to turn the converter on and off.

The TPS54328 incorporates a one-of-a-kind circuit that prevents current from being drawn from the output at startup if the output is pre-biased. When the soft-start commands a voltage larger than the pre-bias level (internal soft start becomes greater than feedback voltage VFB), the controller gradually enables synchronous rectification by beginning the first low side FET gate driver pulses with a short on-time. It then increases the on-time on a cycle-by-cycle basis until it reaches the time specified by (1-D), where D is the duty cycle of the converter. This approach prevents the initial sinking of the pre-bias output, ensuring that VOUT begins and ramps up smoothly into regulation, and that the control loop has time to shift from pre-biased start-up to regular mode operation.

A resistor divider connecting the output node to the VFB pin is used to set the output voltage. TI recommends using divider resistors with a tolerance of 1% or less. Consider employing large value resistors to increase efficiency at extremely light loads; too much resistance is more vulnerable to noise and voltage errors from the VFB input current are more obvious. Below are the corresponding components values that will output the two different types of voltages that are in consideration to power the load cell.

V_{out} (V)	R_1 (kΩ)	R_2 (kΩ)	C_4 (pF)	L_1 (μH)	$C_8 + C_9$ (μF)
3.3	73.2	22.1	5-22	2.2	22-68
5	124	22.1	5-23	3.3	22-68

Table 8: Sample component values for various output rails.

Since the DC gain depends on the output voltage, the required inductance value must increase as the out voltage increases. Voltages above 1.8V require additional phase boot by adding a feed forward capacitor(C_4) in parallel with R_1. The inductor peak-to-peak ripple current (I_{PP}), peak current (I_{peak}) and RMS current can be calculated by equations in the data sheet to tune the performance. The corresponding value of 700 kHz was used for f_{sw} to calculate the appropriate components values. The capacitor value and their ESR determines the amount of output voltage ripple. Therefore, the TPS54328 is design to be used with ceramic surface mount or other low ESR capacitors. Because the buck converter works at median to high frequencies, it is recommended to use 22 µF to 68 µF with low ESR.

Depending on the application, the TPS54328 requires an input decoupling capacitor and a bulk capacitor. For the decoupling capacitor it is recommended to use a ceramic capacitor with a capacitance greater than 10 μF. To increase the stability of the over-current limit feature, TI suggests adding a 0.1-μF capacitor from VIN to ground. The voltage rating of the capacitor must be larger than the maximum input voltage. The TPS54328 is intended to function from 4.5 V to 18 V of input supply voltage. Buck converters require an input voltage greater than the output voltage to function properly. The maximum working duty cycle that is suggested is 65 percent. Using that criterion, the required minimum input voltage is VOUT / 0.65.

8.6.3 Waste Station:

Throughout the design, two options were discussed for the waste station's supply. Powering only the microcontroller, the IR transciever, and a 555 timer using the above design for the water station would be incredibly wasteful. Such low current draw would in theory drop the efficiency, however, it was not observed throughout testing. The first option, which was chosen, utilizes the reference power supply in the sections above. However, if given more time attempting to power the station by batter could be viable. The choice of a battery-based supply introduces the convenience of not needing the litter box near a wall. It also introduces the need to replace the battery every few weeks or months. The power breakdown for the waste station is provided in the table below.

Component	Max. Current (mA)	Approximated Max. Current (mA)	Voltage Rail (V)
ESP8266	170	400	5
LM555	15	N/A	5
TSSP4384	5	N/A	3.3

Table 9: Waste Station Power Table.

Again, the ESP8266 power consumption is assumed to be 400 mA due to the uncertainty regarding the absolute maximum supply current. As for the 555 and IR reciever the current requirements are quite low, and the respective data sheets provide an absolute maximum. Hence, the N/A is used to indicate the absolute maximum supply current is actually the maximum supply current. The TSAL4400 is not included since it will be driven by the output of the 555. The net current the supply would provide is approximately 420 mA, which is much below the 1.5 A design of the water supply. In a low-power mode it is quite likely for the supply to source below 100 mA and for the efficiency to fall to near 40-50%. The high power for the ESP is primarily due to the wireless transmissions implying that an optimization could made to the frequency that data is sent back to the base station to accommodate a battery supply. However, further testing will be needed to confirm, but the maximum net power will be in the ballpark of 2W.

8.6.4 Base Station:

The Raspberry Pi will be powered externally a microusb wall plug. For simplicity, a power supply was not designed for the base station. Attempting to characterize the Pi enough to adequately design a supply around it would present significant time and resources for very little gain. From the user's perspective, the base station will remain fixed in the house and a simple USB wall plug can be used to power the station effectively.

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9 System Software Design

To develop these systems, we will choose software that can run on ordinary PCs, so that we can develop the software in a familiar environment to quickly iterate and fix bugs. Testing of protocols will be done through the use of design software simulations of each subsystem, that send realistic data to the base station software and respond to commands appropriately. We can also run the web server and database on an ordinary PC, so the whole system can be developed in a prototype environment before moving to real hardware.

9.1 Base Station Server Architecture

The base station runs 4 main components. The first two are the frontend and backend API, which together form the outward facing interface of the base station. The frontend presents the user interface, and the API allows information to be saved and retrieved from the database. The database, using MongoDB, is another component of the base station. The final component is the Linux OS itself, which is responsible for hosting the wireless access point, assigning IP addresses, and resolving hostnames.

9.2 Communication Protocols

To facilitate communication between each subsystem and the base station, the base station will provide a private Wi-Fi network that each device will connect to. The user will also connect to this network to access the front end. This means we will need to configure the base station as a router, and it must be capable of handling DNS requests. This can be done in a Linux operating system. The base station can run a DNS server that allows names to be resolved to those IP addresses.

HTTP is used to carry updates from the stations to the base station, and to retrieve the most up-to-date information. This allows us to use a well-established protocol, and to unify the API between the subsystems and the frontend.

The food and water stations will regularly report the current count of how much food the cat has eaten. The litter system is different in that it only updates on litter box events, so it does not need to continuously update the base station. Because each station updates regularly at an interval of 5-10 seconds, polling can be used by the subsystems to get the most recent information from the base station.

9.3 Feeding Station Design

The firmware design of the feeding station is intended to be as autonomous as possible. The feeding station can operate completely independently of any other station in the system. It does this by maintaining its own schedule with periodic internal interrupts. If the base station is available, it will retrieve the desired shcedule from it, but otherwise it will use a default schedule to ensure that it continues to operate.

At a regular interval, the food station will wake up and check a number of conditions. At the end of every day, the feeding station will retrieve the latest schedule from the base station. This is done to ensure that the schedule does not change mid-day, prevent the cat from being over- or underfed. The station then reinitializes itself for the beginning of the next day. If it is a scheduled feeding time, the station will calculate the appropriate weight of food to dispense, then dispense it. Measures are in place to prevent overdispensation. After checking for the above conditions, the station will take a weight measurement and calculate the cumulative sum of how much the cat has eaten, and then will report that to the base station.

9.3.1 Daily Reset

At the end of the day, the station first updates its schedule and synchronizes the time with that of the base station, which has an accurate real-time clock for timekeeping. If the request for an updated schedule fails, it will retry on the next interval. After the new schedule is retrieved, The station will measure how much is left in its bowl and use that value as the starting weight, and it will reset its dispensed amount to zero.

9.3.2 Scheduled Food Dispensing

The station has a minimum amount of food it can dispense, and it will never dispense enough food to overflow the bowl. If the amount of food is too small to dispense, it will skip this branch and wait for the next interrupt. If the amount of food is too large to dispense without overflowing the bowl, it will clamp that value and continue, unless the clamped value is too small to dispense. It will then dispense the food and then update the dispensed value in order to accurately calculate the cumulative total of what the cat has eaten.

9.3.3 Regular Measurements

At every interval, a measurement is taken of the current weight of food in the bowl. The cumulative amount eaten by the cat is the difference of the sum of the starting weight and the dispensed weight, and the current amount in the bowl. In the case that the current amount is measured to be too large, such as if a foreign object is resting on top of the bowl, the cumulative weight may be calculated to be negative. If this occurs, an alert will be sent to the base station instead.

9.3.4 Initialization

Initialization occurs when the feeding station first powers on. There are two possible actions that can fail when initializing: failure to connect to the network, and failure to connect with the base station. If either of these fails, subsequent networking steps are skipped and a default schedule and time is put in place. Additionally, flags are set to attempt to reconnect or retrieve the correct schedule from the base station upon the next interrupt. After those steps are completed, the inital weight and dispensed weight are initialized to the current weight and zero, respectively.

If either of the reconnect flags are set, the feeding station will again try to connect to the wireless network or retrieve the feeding schedule. The same timeout is used, and if a timeout occurs, the flag will be reset and the feeding station will attempt to connect again on the next interrupt. The reconnection step does not prevent the rest of the station from operating, it only incurs a delay on each interrupt while waiting to connect to the network or retrieve the schedule.

9.3.5 Taking Measurements

To measure from the load cell, an external ADC is used to amplify the differential signal from the load cell and convert it to a highly accurate 24 bit value. It uses an SPI-like protocol to communicate, which had to be implemented manually using GPIO pins.

When a measurement is made, the result is verified to make sure it is accurate. First, if the measured value is significantly negative, this indicates that the user has removed the bowl for cleaning, and the recalibration flag is set for the next time the bowl is detected, after the user replaces it. If the reading is beyond a reasonable measurement for the load cell, an alert is sent to the base station indicating either extra weight was added to the system, or the load cell is faulty. In either of those cases, the motor is stopped if it was running before, and the system aborts any current processing and waits for the next interrupt. If the measurement is good, the weight is stored as the last known good value, and if the recalibration flag is set, the system recalibrates the load cell from a known value.

Recalibration occurs when the empty bowl is placed on the load cell. Since this is a known weight of zero, it provides an opportunity to tare the load cell back to an accurate zero. In addition, any food that was in the bowl previously is thrown out when the user cleans it, so the last known value must be subtracted from the dispensed amount to account for its disappearance, since the cat did not eat it.

9.3.6 Dispensing Food

To dispense food, a feedback loop from the load cell to the dispense motor is established in software, and the dispensation occurs in two stages. First the motor runs in the forward direction, then it rapidly alternates directions to prevent food from getting stuck. When the weight in the bowl is at the desired amount, the motor is stopped. Timeout is possible if the food hopper runs out and becomes empty. In that case, the motor will not be able to dispense food and the weight will not increase. If that occurs, the food station will abort its dispensation and send an alert to the base station.

9.4 Water Station Design

The firmware design of the water station is very similar to that of the feeding statoin, and is also designed to be as autonomous as possible. The water station can also operate completely independently of any other station in the system. Unlike the feeding station, it does not require any kind of schedule, but it will use periodic interrupts to control its actions.

Similarly to the feeding station, the water station operates on intervals. At the end of every cycle, the water station will resynchronize its time with the base station. The station then reinitializes itself for the beginning of the next day. If the water in the bowl is detected to be too low, the station will calculate the appropriate water to dispense to fill it up, then dispense it. Finally, the station will take a weight measurement and calculate the cumulative sum of how much the cat has drank, and then will report that to the base station.

One difference between the feeding station and the water station is the conversion of weight to volume. The density of pure water is approximately 1 gram per milliliter. According to the United States Geological Survey (USGS) the density of tap water is dependent on temperature. From 40 $\deg F$ to 90 $\deg F$ the density varies by half a percent. For our purposes, a density of 1 g/ml will be assumed. Therefore, the conversion from volume to weight is automatically done. The weight sensor will output the weight of the bowl in grams which indirectly measures the volume in the bowl.

9.4.1 Initialization

Initialization occurs when the water station first powers on. There is only one possible action that can fail when initializing, failure to connect to the network. If failure does occur, subsequent networking steps are skipped and a default time is put in place. Additionally, a flag are set to attempt to reconnect to the base station upon the next interrupt. After those steps are completed, the inital weight and dispensed weight are initialized to the current weight and zero, respectively.

If the reconnect flag is set, the water station will again try to connect to the wireless network. The same timeout is used, and if a timeout occurs, the flag will be reset and the water station will attempt to connect again on the next interrupt. The reconnection step does not prevent the rest of the station from operating, it only incurs a delay on each interrupt while waiting to connect to the network.

9.4.2 Dispensing Water

The water station dispenses water in a similar way to the feeding station, but since there are no obstructions in the water tubes, the pump can be run continuously. To dispense water, a feedback loop from the load cell to the pump is established in software. The pump runs while the load cell makes periodic measurements. When the weight in the bowl reaches the desired amount, the pump is stopped. A timeout is possible if the water reservoir runs out and becomes empty. In that case, the pump will not be able to dispense water and the weight will not increase. If that occurs, the water station will abort its dispensation and send an alert to the base station.

9.5 Waste Station Firmware

The firmware design of the waste station is relatively simple. Due to the retrofitting onto either an already operable automatic litter box, or traditional litter box, the motor driving control is not necessary. Refer to Chapter 8 for a more explicit hardware overview, but the core components interacting with the system controller are an IR sensor and humidity sensor. If the IR beam is interrupted, the system controller will emerge from an idle state, and notify the base station of a waste event, and whether it is urination or defecation. A humidity sensor is sensed for a finite duration of time to detect whether the cat is urinating or defecating. If the humidity increases significantly, it is likely that the cat has urinated. External testing with the chosen humidity sensor is needed to verify and characterize the urination threshold.

In order to prevent multiple detections from one waste event, a timeout is present after the first interruption of the IR beam is detected. That way, if the cat interrupts the beam multiple times during the same event, it will still only count as one event. It is very unlikely that a cat will use the litterbox multiple times within just a few minutes. The timeout is not directly implemented but implicit in the humidity sensor measurement. When the IR detection interrupt occurs, humidity measurements began almost immediately for several minutes. During the measurements additional interrupts do not stack and are subsequently ignored.

To facilitate cleaning by the user, an external switch can be flipped which will disable the logging functionality. As long as the switch is in the ”change” position, the waste station will not log any interruptions of the beam as waste events. To change the litter, the user simply flips the switch, replaces the old litter with new litter, and then flips the switch back, and the system is ready for use again.

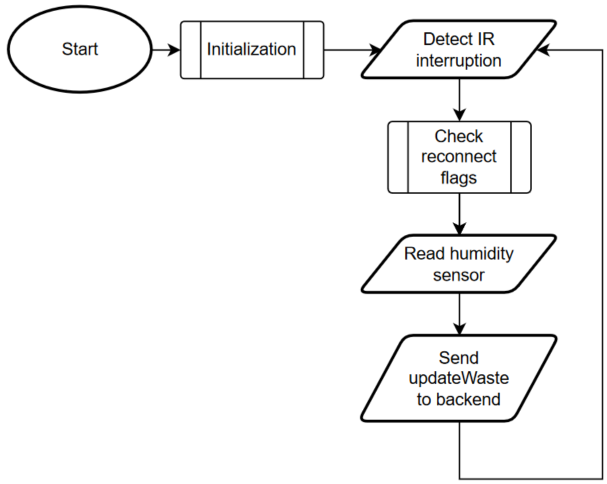

Figure 39: High-level waste station firmware flow chart.

9.6 Subroutines

The waste station only has a few subroutines: Initialization and Check Reconnect Flags. Both are simple, and both are fairly similar to each other.

9.6.1 Initialization

The initialization procedure is simple. All the station must do is connect to the wireless network. If it is not possible, the station will set a reconnect flag to try again on the next waste event.

9.6.2 Check Reconnect Flags

The reconnection procedure is essentially identical to the initialization procedure. The waste station simply attempts to connect to the wireless network again, and if there is a timeout, it will continue and try again later.

9.6.3 Humidity Measurements

The humidity measurement subroutine takes humidity measurements and computes statistics on the measurements for 3 minutes. This limit of 3 minutes also corresponds with the aforementioned timeout after a proximity event has occurred. Immediately after the proximity event occurs the initial humidity in the litter box is captured. Denoted the snapshot humidity, it represents the start point or calibration of the measurements. Throughout the 3 minutes the average

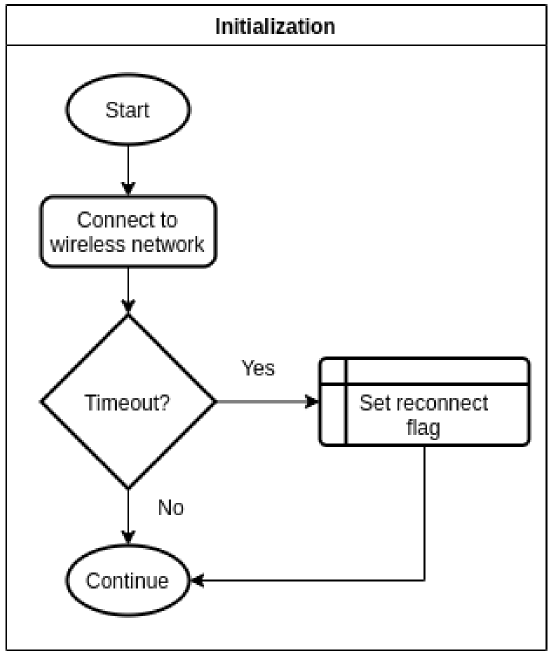

Figure 40: Waste station firmware initialization flow chart.

and maximum humidity are measured. If the maximum humidity is sufficiently greater than the snapshot humidity by some arbitrary threshold, 3% relative humidity was chosen, it is implied the cat urinated. Otherwise, the lack of humidity increase implies the cat defecated.

9.6.4 Proximity Interrupt Handling

Every feature and functionality of the waste station stems from the proximity sensor being interrupted. High-level, the proximity sensor triggers an interrupt for the station to begin detecting the humidity. The main loop executing on the ESP polls the proximity interrupt after initialization. When an event occurs, the humidity measurement subroutine is executed and the results of urine or excrement is transmitted to the base station and both the total uses and type are logged for the user.

9.6.5 Error Handling

While not explicitly a subroutine, this section includes several bug prevention mechanisms in the firmware. The most susceptible bug is the resetting of the interrupt. Once the transmission has been attempted with the base station the interrupt flag is reset and another proximity event may occur. The waste station takes a fire-and-forget approach and does not verify if the base station received the update request. The lack of acknowledgement was made from simplicity and

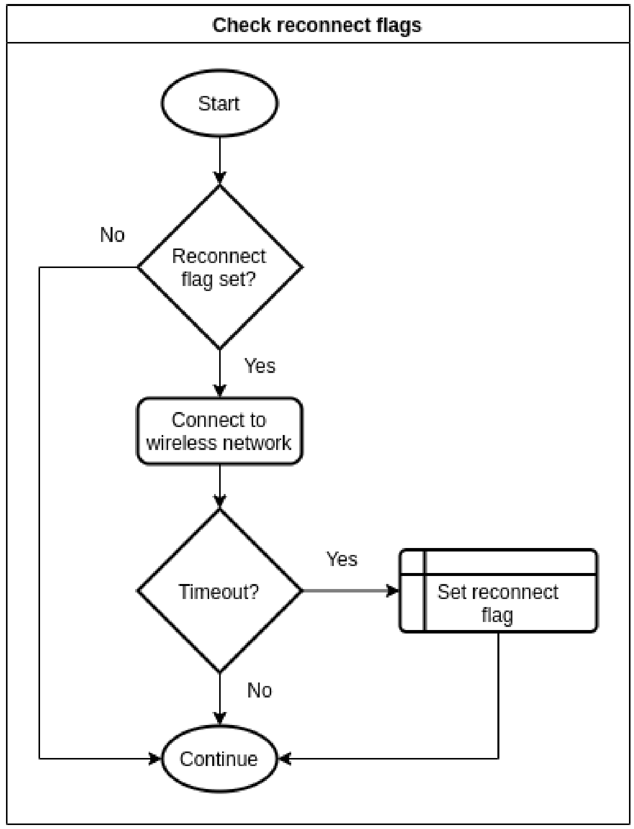

Figure 41: Waste station firmware reconnection flow chart.

future improvements would address an acknowledgement mechanism in case the base station is temporarily disabled.

The other source of significant error is in how the cat enters the litter box. Refer to the final demonstration for more information, however, if a litter box is uncovered then there is no guarantee the cat will enter the box from a certain angle. It could occur that the cat enters the box and smells nearby the humidity sensor. The increased moisture in a cat's nose will cause the snapshot humidity to read larger than the actual humidity. If so, the current humidity will decrease somewhat with each measurement. If the humidity increases substantially, 3% relative humidity for 5 samples in a row is the current implementation, the snapshot humidity will update to the current humidity. Again, the feasibility in using a humidity sensor to detecting urine or excrement is debateable. However, in the general case it should be good enough.

9.7 Network Architecture

The system network will be completely self contained. This allows for complete control over the network. The base station will provide a wireless local area network access point with a predetermined SSID that all the substations will be able to connect to. The base station will also provide DNS services, which will allow the user to easily connect to the frontend running on the base station.

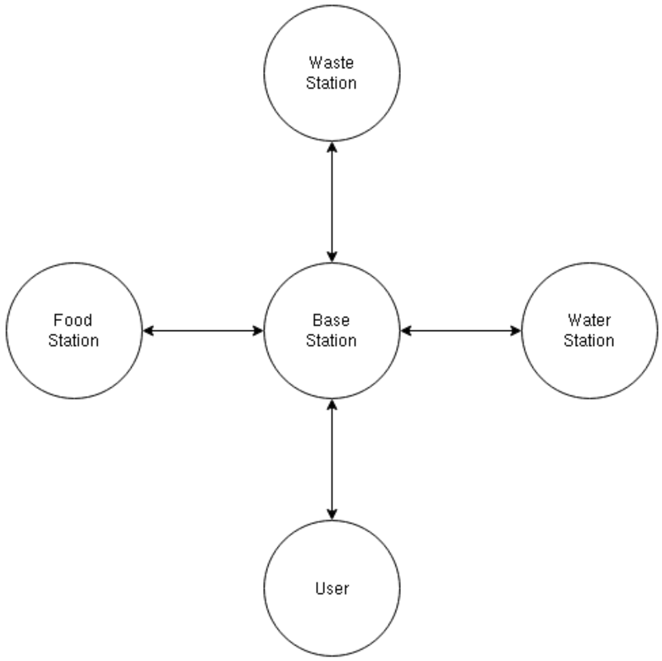

Figure 42: Network diagram showing the star structure

Since the base station forms the central component of the network, the network as a whole takes on a star-shape. Because of this, if any substation fails, the rest of the system can continue operating. However, if the base station were to fail, a problem could occur if the substations relied on it for their operation. To combat this, each substation is designed to be as autonomous as possible. Each one will operate consistently without any network connection at all, and in the case of the food station, it will be able to remember its schedule so it does not need to rely on the base station for food dispensation timing.

9.8 Database Design

Data storage: The purrfect cat care system supports a few functionalities, particularly changes in cat behavior. This presents the designers with a few challenges, how the data should be tracked, how much space should be considered for a prolonged duration of data persistence, and what is the most efficient mode of data management. We look at a couple of options for storing and manipulating possibly large quantities of data. The choices available for logging input data are file system storage, or database storage. We discuss the differences for each and decide which one is the best to use for this application.

File System Storage: Data can be stored in files and saved onto the hard disk. These files can be updated, deleted, or moved in the hard disk by users. The files live in a directory, which can have other files or other directories. Storing data in a file can provide fast and easy access to the data if limited to small amounts of data and organized in a way that the data can be sorted through efficiently. No additional overhead or software is required for using this form of data storage, making it an ideal low cost solution and easy to use [138]. The problem occurs when the data grows in complexity and size. The issue of redundant data can occur when the same data is repeatedly used in related elements [137]. For example, the purrfect cat care system will need to keep track of how many times the cat uses the litter box and how much food and water is consumed within one day. For every day when one of those values needs to be added, the date will be recorded in every data element. As the data grows, this redundant data can use up precious memory space. Also, as these files become larger, the data will use more system resources to access and therefore become slow. Furthermore, the file system does not have any type of change history and therefore if the files are moved or deleted by accident or malicious intent, there is no record of the original file [138].

Database: Rather than storing data in files, a database stores data in a collection of organized structures. A database can be visualized as a set of tables containing rows and columns or as a collection of key-value pairs. This structure allows for data to be searched, or queried, easily. Databases are generally ACID compliant, where ACID is an acronym for atomicity, consistency, isolation, and durability [111]. ACID compliance means that the database will contain all four properties and that is that the data will be reliable, validated (i.e. the data can be rolled back if something went wrong), and the system can be scalable, and if it fails, nothing will happen to the data. A database can be either relational or non-relational.

Relational: A relational database is organized as a set of tables, where each can contain a relationship to the other tables in some way. Most relational databases use structured query language (SQL), which is a programming language, to access the data elements in the tables [121], which is why the terms SQL and relational are interchangeably used when discussing these types of databases. Relational databases are generally designed to be normalized, meaning any redundant data is removed and the tables will be split into smaller tables based on the relationships between the data to optimize disk space. The organization also allows data to be inserted, deleted and updated more quickly. SQL databases prioritize consistency and reliability in the data over availability and speed [54].

Non-relational: A non-relational database is organized in documents or objects containing key-value pairs. Unlike relational databases, non-relational databases are designed to be denormalized, which is why they are also called noSQL databases. This means the data is combined and often redundancies are added for faster querying [133]. Because of this redundant data, non-relational databases may require more disk space to store the data. However, since the data is organized as more of a document, the databases are more scalable horizontally. Also, non-relational databases prioritize availability over consistency and therefore may lose data integrity.

Database management systems: A database management system (DBMS) is the software that interfaces with the database and allows users to set up and manage the database. This makes the database upkeep more manageable and provides the ability to monitor performance and database metrics [27]. Two DBMSs considered for this project are MongoDB and MariaDB. MongoDB uses a noSQL non-relational database and organizes the records into structures called documents which can be accessed from any language that they are written in [26]. MariaDB uses a SQL relational database and uses SQL to query the data. MongoDB will have faster access, but Maria DB will have faster insertion, deletion and updating of the records. One of the decision factors is the tradeoff between speed of access and total disk space needed with the data and overhead.

Comparison and analysis: To decide on which type of data storage to use, we must first look at the requirements of the system. The purrfect cat care system base station should run autonomously. The inputs from the other systems (i.e., the water, food and waste stations), should be handled by the base station software automatically. The data should be readily available by the base station software to do statistical calculations and report the daily results back to a user via a web application. Since the data will need to be accessed efficiently by a software program rather than manually, the file system storage is not the optimal choice. Then comes the choice between the database designs. When looking at the types of databases, we need to see how the data will need to be organized. For each of the systems connected to the base station, the data will be mostly log data as shown in figure [138]. Considering the few relationships between the tables, the data may benefit from being organized in a non-relational database. The next factor to consider before choosing the best database design structure for this project is whether speed or space is more important for the purrfect cat care database management system. We look at the individual stations and their data that will be transmitted to the base station.

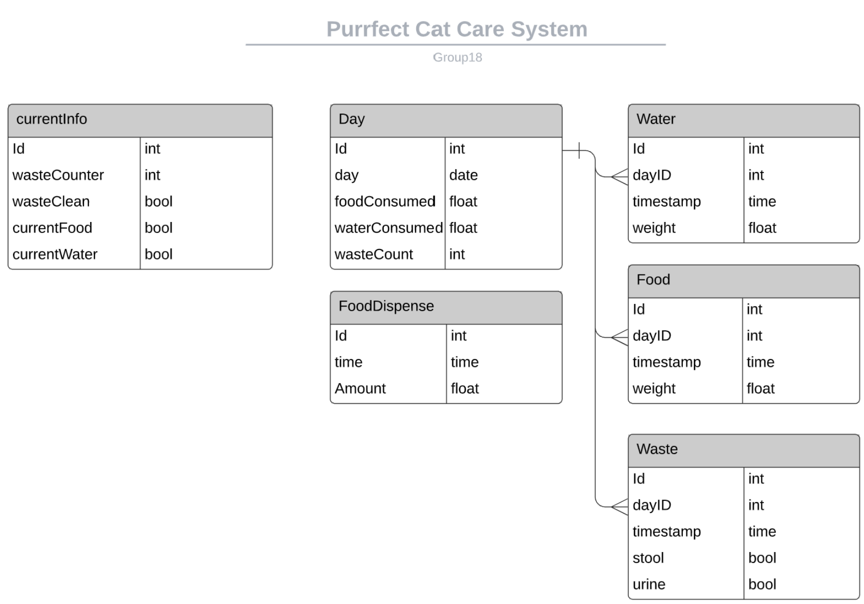

Figure 43: Entity Relationship Diagram

Feeding station: The feeding station will be configurable to have up to a maximum of six scheduled dispenses of food to the bowl per day, set by the user on the application. These configurations will be stored in the database. For each time the food station dispenses food, the system will also send an update to the base station database of how much food was dispensed and how much food was consumed from the last time it checked in, at the same time. Therefore, the total values being sent to the base station will be twelve double precision float values per day, plus the initial configuration values which will be a combination of time-date values and double precision float values.

Water station: For the water station, there will be a set total of six samplings per day which reports back to the base station database how much water was consumed by the cat from the last check-in and the dispensed amount. The water station will keep the bowl filled up to a maximum amount and will not have any configurations from the user stored in the database. Therefore, the total values being sent to the base station will be twelve double precision float values per day.

Waste station: The waste station will track how many times the cat enters to use the litter box and whether the cat defecated or urinated. The update to the base station database will be the count increase for litter box usage each time the cat enters the litter box and a Boolean value that determines whether the cat defecated or urinated. To determine how many updates this translates to in the database, we need to look at how often the average adult cat visits the litter box. Generally, an adult cat will go to the litter box to urinate two to three times per day and will defecate about once per day. Therefore, taking the ceiling of these values, the system will potentially send up to eight updates per day to the base station, four Boolean values and four integer values.

Choice of data storage system: Using these values we can determine the total number of updates needed per day to the database which will be used to determine how much space will be needed on the base station system to retain the data for twelve months before being purged. Considering the requirements discussed, the database should expect to have about 8,766 double precision float entries, 1,460 integer entries, 1,460 Boolean entries, and 6 configuration entries if only set once for a twelve-month period. Looking at the data alone without any overhead from the database management systems installation, the amount of storage space needed for these records when considering how much space is needed for each one, we need about 76 kilobytes of space for the data. Comparing the space needed to the available disk space on the base station, which will be at least 64 gigabytes, the space is not a significant factor, therefore speed of access would be the better option to maximize user experience. The best option for this would be a non-relational database management system like MongoDB.

9.9 Interface Layer Design

An interface is a layer that allows two software components to talk to each other. Since the Purrfect Cat Care system will have many systems interacting with each other to exchange in-

	Structure	Speed	Disk Space	Data
MongoDB	non-relational/ noSQL	Faster data access	More usage	Focus on availability
MariaDB	Relational/SQL	Faster data manipulation	Less usage	Focus on consisitency and reliability

Table 10: Database comparison

formation, this will be a necessary layer to have. An interface layer needed for this design is the application programming interface (API) which facilitates communication between the database, the user frontend, and between the wireless modules on each of the subsystems.

APIs consist of a collection of endpoints, which are specific functions that communicate data via a request and a response. It is also a way to separate business logic from the presentation layer. To display the historical and statistical data collected from the substations, the base station will require an API layer to communicate the information stored in the database to the user application. Typically, any heavy calculations will be performed in the API layer and then returned to the frontend application rather than performing the calculations in the frontend to avoid any slowdowns on the application layer. However, the calculations being done are minimal and will not slow down the frontend, and the device accessing the frontend will have more memory than the server being hosted on the raspberry pi. Therefore, the API will only pull the data stored in the database and any statistical analysis will be delegated to the frontend application.

In addition to providing data to the frontend, the API will act as the go-between for the substations and the database. Each substation will report their sensor data to the base station on a regular scheduled time, which will then be stored in the database for later processing. Furthermore, the food station will need to know its schedule for dispensing food as well as the amount needed to be dispensed based on the information provided from the user on the application. Therefore, the substation will need to make a request to the API for that information stored in the database. The core endpoints are discussed in more detail below.

To understand which endpoints and how many will be needed, it is important to understand what tasks they will need to perform and how often they will be called. Starting with the communication between the front end and database, an endpoint will be needed to record any user inputs from the application. Specifically, the user will input up to five different scheduled times in hours and half hour increments for the daily dispense, combined with an amount to be dispensed in grams. These values will be stored in the database as an array.

Many API endpoints come in pairs, as there needs to be an endpoint for both directions of communication, therefore, an endpoint will also be needed to retrieve the schedule and dispense amount to display on the application to the user. This endpoint can be used by both the frontend as well as the food station during initialization and for any subsequent updates of the food schedule and dispense amount by the user. As one of the important objectives for the Purrfect

Cat Care system, each of the substations should be completely modular and therefore have very little dependence on the base station, therefore, this endpoint will be important for the substation to make the call when it needs to and not require any prompt from the base station to get setup. Furthermore, in order to display the cat's statistical data on the application, an endpoint will be needed to retrieve the sensor data collected from each of the subsystems.

The API will also need to have communication with the subsystems as mentioned before, however, to keep with the modularity of the subsystems, the communication will flow in one direction, from the subsystems to the base station. An endpoint will be needed for each of the subsystems to call to send their sensor updates to the base station. Also, since the system as a whole will not be connected to the internet, there will need to be some way to synchronize the time and dates between systems. Therefore, an endpoint that returns the date and time from the base station will also be required. There will also be one endpoint to handle any alert coming from the subsystems for any error in dispensing, or sensor reading that may show signs of the system needing manual interaction to continue service of the system, for example, if the food or water reservoirs were detected as being empty and need to be refilled to continue working properly and alert would need to be sent to the user via the application to alert them of this need. Table 11 shows a summary of the endpoints needed for the Purrfect Cat Care System.

An interface will be needed to communicate the sensor data from the sensor components to the microcontroller it is connected to. The hardware software interface will be on the embedded systems layer of each of the subsystems and will interface with the serial communication to the wireless module in order to send updates through an HTTP requests directly to the base station. The firmware on the wireless module will be coded to broadcast sensor data wirelessly over WiFi to the API once collected automatically. The firmware design is discussed in greater detail under the firmware design section.

(Intentionally left blank)

EndPoint	Incoming	Outgoing	Description
setSchedule (POST)	[{ enabled: boolean, hour: string, minute: string, tod: string, amount: number }]	error, success	Updates the database with the schedule array containing the dispense time and amount.
getSchedule (GET)	{}	[schedule { enabled: boolean, hour: string, minute: string, tod: string, amount: number }]	Returns the schedule array with the dispense time and amount.
updateFood updateWater	{weight: number}	error, success	Updates the database with the station sensor data.
updateWaste	{type: [stool, urine]}	error, success	Updates the database with the waste station sensor data.
getWater getFood	{dateRange: string}	[{ _id: string, dateString: string, timestamp: string, weight: number }]	Receives a dateRange code of either ”today”, ”week”, or ”year” and returns the collected sensor data from the database for a data range.
getWaste	{dateRange: string}	[{ dateString: string, urine: number, stool: number, total: number }]	Receives a dateRange code or either ”today”, ”week”, or ”year” and returns the collected sensor data from the database for the date range.
setAlerts	{alertType: string}	error, success	Updates the database with the specified alert type. Alert is overwritten if it already exists.
getAlerts	{}	[{ _id: string, type: string, dateCreated: string, msg: string, title: string, viewed: boolean }]	Returns all of the alerts set on the system
viewedAlert	{alertType: string}	error, success	Updates the ”viewed” field to true on the specified alert.
deleteAlert	{alertType: string}	error, success	Deletes the specified alert.
setDueDates	{dateKey: string}	error, success	Updates the database with the special date for timed events such as weekly clean litter box alerts.
getDueDates	{dateKey: string}	last access date	Returns the special date saved in the database.

getDate	{}	{
		date: number,
		hour: string,
		minute: string
		}
			Returns the current date’s day, hour and minute.

Table 11: API Endpoints

10 Component Characterization & Prototyping

Many of the sensors and devices used throughout this project have not been used before by the team. To best understand how these devices work, testing throughout Senior Design 1 was done to better understand their behavior, linearity, and investigate potential design concerns. This chapter outlines the procedures followed to determine the operating parameters of various hardware components, and the calibration of such components.

The following sections do not comprehensively cover all initial prototyping and testing which was done throughout the project. During Senior Design 1, all core components were purchased and prototypes were build on breadboards. For the sake of this already lengthy report, only the systems which were most unfamiliar to the team will be included in this characterization and prototyping. In general, our approach was to rapidly iterate on the prototype circuits instead of focusing heavily on the theory. However, theory was used heavily in arriving at approximate values for components.

10.1 Load Cell

The initial concern with the load cell was that a 5 kg cell would not provided the needed resolution to distinguish variations in individual grams. The option to use a lower capacity cell, such as a 1 kg or 500 g cell were available, however, the ultimate capacity was not much greater than the rated capacity. The ultimate capacity defines the maximum amount of weight before the cell permanently deforms. For example, the TAL221 is a 100 g load cell, from the same product line as the TAL220B, features an ultimate capacity of 200 g. If some unknown object were to fall into the bowl, the cat decides to press their paw into the bowl, or someone stubs their toe on the bowl then it could permanently break the scale.

Other concerns stemming from the capacity included the linearity of the load cell. Ideally, the 5 kg cell with a 3.3 V excitation will be linear over the 5 kg range; $\frac{0.66\mu V}{g}$. However, linearity of the cell is dependent on the strength of the deformation. When operating in the sub-1 kg range one would expect the transfer characteristics to be linear. If the cell exhibits high non-linearity then large loads, lets say in the 4 to 4.5 kg range, would deviate from a linear curve. The non-linearity is a non-issue since the scale will operate on the order of a few hundred grams. However, if the accuracy of the 5 kg cell had not been sufficient then decreasing the capacity to 1 kg could have introduced these problems.

10.1.1 Proof of Concept

As a proof of concept, a 5 kg integrated strain gauge load cell was purchased. Integrated is used in the sense that the load cell, HX711, and all supporting circuitry were integrated into a single product. Four wires connected to the HX711 breakout board: V_{cc}, GND, SCK, and DT. The SCK and DT pins stand for serial clock and serial data respectively. The HX711 uses SPI to interface and communicate with a microcontroller. From the HX711, the breakout board connects to the excitation and sense wires of the load cell.

The Arduino Nano Every was used to drive the load cell and to prototype the firmware. The 5V and GND pins of the Nano were connected to the V_{cc} and GND lines, respectively. The SPI lines for the nano correspond to pins 12 and 13 for DT and SCK. A non-Arduino microcontroller could be used as long as it supports an SPI interface. The minimum working prototype uses an HX711 Arduino library to handle signal processing. The library was created by Bogdan Necula and is freely available on the library manager.

Time was spent searching through the library source code to determine class fields, methods, and proper usage. The key points include methods such as: initializing the data and clock pins, setting the calibration factor, taring the scale, reading the current scale value, and setting a true zero of the scale. The calibration and reading process were the key parts of this prototype. The validation was broken into three parts: 1. Driving firmware, 2. Calibration, and 3. Error minimization.

Driving Firmware

The library treats the load cell as a HX711 class. The class is instantiated with pins numbers for the data and clock lines. For non-Arduino microcontrollers this will not be necessary. The respective lines will have traces to microcontroller's GPIO pins. The class has a field for a calibration and offset factor. The calibration factor is an integer that can be set by the program to determine the scale of measurement. For example, a scale factor of 1 could measure between 0 and 1, whereas a scale factor of 100 could measure between 0.00 and 0.01. This value will vary on the full scale reading of the load cell and must be determined experimentally. The offset factor is subtracted from each measurement to account for taring of the scale.

The calibration and offset factors are not necessary to receive an output from the cell. As long as the cell has been instantiated, the get_ units method returns the current measurement of the scale. The HX711 has a 24 bit ADC implying a 24 bit value will be returned. The value of the cell's output has little value without a proper calibration. Surprisingly, calibrating the cell is incredibly simple.

Zero Factor

Zero factor measurement is an ongoing measurement or calibration. Each time the load cell is powered on the cell will read some value. Assuming the cell has no load placed on it, the measured weight is the approximate zero of the scale. If a bowl is placed on the scale and this measurement is made, the weight of the bowl will be eliminated from the measurement. For this initial prototype a bowl was not included. The library does include a tare method which does the same process, but there is a slight difference in the flow of the firmware.

The key difference between the tare and manual calculation is the accuracy to which you want a true zero. Several measurements can be averaged at initialization to determine an accurate zero value. For the ultra precise, statistical methods may be used to minimize the error to within some error bars. Over time, the zero factor can be updated at the start of each day to keep the offset from falling out of calibration. From a system error perspective, the error associated with the zero factor is negligible. Since the zero offset is subtracted from every measurement it is an error present within every measurement.

The zero offset could be a powerful way to counteract the creep of the load cell. Mentioned in the core technologies investigation, the output of a strain gauge load cell will drift, or creep, over time. If a 100g weight is left on the load cell, over a span of a half an hour an error on the order of 5-10 grams could be noticeable. The creep will be determined experimentally, however, the zero offset could be done a moment before the cat begins to eat from the bowl. Assuming a cat does not sit at the bowl for 30 minutes eating, the weight measured sometime later will be negative. Ignoring the sign gives the net weight of food lost. At the time of writing this, the creep experiment has not been done but could be a viable way to increase system accuracy.

Calibration

To calibrate the sensor, a known mass is needed. The cell was calibrated to a 1 kg load. A set of PASCO 10 g to 1 kg weights were readily available. The load cell has a maximum rating of 5 kg. The choice of a 5 kg maximum was to protect the device for the rare instance an animal, or owner, were to step on the bowl. If this maximum weight is exceeded the strain gauges could be permanently damaged. The expected measuring interval will be between 0 to 1 kg. The calibration and offset factor are seen only from the microprocessor and setting the two factors will not physically change the load cells analog output. The calibration is necessary for the microprocessor to make sense of the digitized signal received.

Finding the calibration factor was a slow and repetitive process. Within the Ardunio loop function a user input would change the calibration factor by a fixed amount. The initial calibration factor was set to 1 000 000. This choice was made with the idea that a 24-bit output would be on the order of millions when no load was present. Interestingly, the calibration factor would be much less than a million. A coarse iteration was done with factors of 10 ending at 100. Between the 1000 and 100 measurement the measured weight passed the 1 kg threshold. This process was continued decreasing the increment value until a final value of 461.66 was reached.

The desired accuracy is to measure to an accuracy of a quarter to a half of a gram. With the above calibration, a null measurement oscillated about ± 150 mg. Sometimes a negative weight is measured but this is an artifact of how the calibration factor and offset are used to calculate the measured value. With the system calibrated a set of PASCO weights were used to verify the measurement.

Verification

The expected operating mass of food the load cell will measure is on the range of 0 to 60 grams;

0-2 ounces. The smallest weight available was a 10 gram hook weight. Hence, 10 gram intervals were measured from 0 to 50 grams. However, an ideal experiment would use on the order of 2.5- 5g weights to verify. Once the input mess reached 50 grams, the resolution was changed to 50 gram increments. The plot of expected and measured weight, as well as the list of data points are been provided below. The list is provided since it is difficult to determine the error associated with each measurement. In summary, the maximum error between any measurement 0.546 g. Each entry in the following table is given with units of grams, g.

m_{in}	$m_{o,max}$	$m_{o,avg}$	$m_{o,min}$	m_{in}	$m_{o,max}$	$m_{o,avg}$	$m_{o,min}$
0	-0.023	0.048	0.095	450	449.817	449.901	449.713
10	10.020	10.111	9.951	500	499.892	500.039	499.729
20	20.099	20.144	20.003	550	549.640	549.765	549.548
30	30.174	30.229	30.069	600	600.148	600.277	600.015
40	40.193	40.295	40.139	650	649.898	649.982	649.797
50	50.254	50.335	50.174	700	699.719	699.788	699.63
100	100.210	100.310	100.097	750	749.493	749.748	749.379
150	150.001	150.088	149.923	800	799.944	800.045	799.887
200	200.224	200.301	200.145	850	849.77	849.99	849.444
250	249.969	250.142	249.932	900	899.246	899.300	899.177
300	300.364	300.429	300.299	950	949.815	949.947	949.715
350	349.822	349.904	349.767	1000	1000.464	1000.58	1000.316
400	400.029	400.117	399.894	N/A	N/A	N/A	N/A

Table 12: Load cell verification measurements.

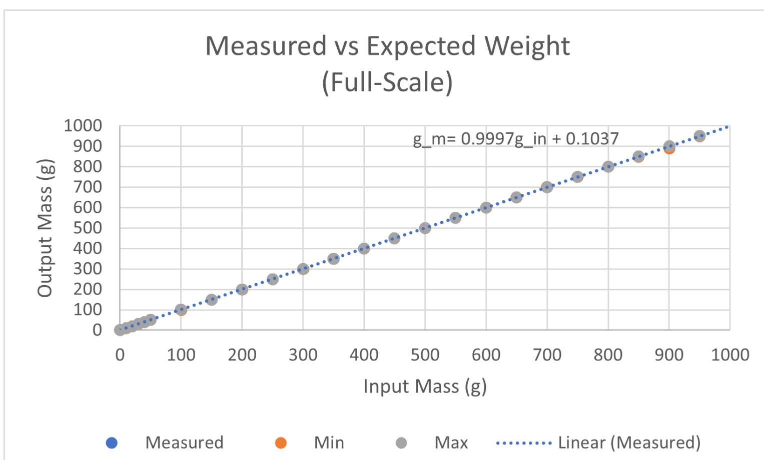

Figure 44: Plot of weight measurements from Table 4.

Mentioned above, the primary purpose of the load cell is to measure a full-scale weight of approximately 100 grams. The behavior of the system at weights beyond approximately 300-400 grams is not necessary since the intended food bowl is much less than several hundreds of grams. Therefore, an additional plot with the measurements from 0 to 100 grams is provided to further iterate the linearity of the measurements.

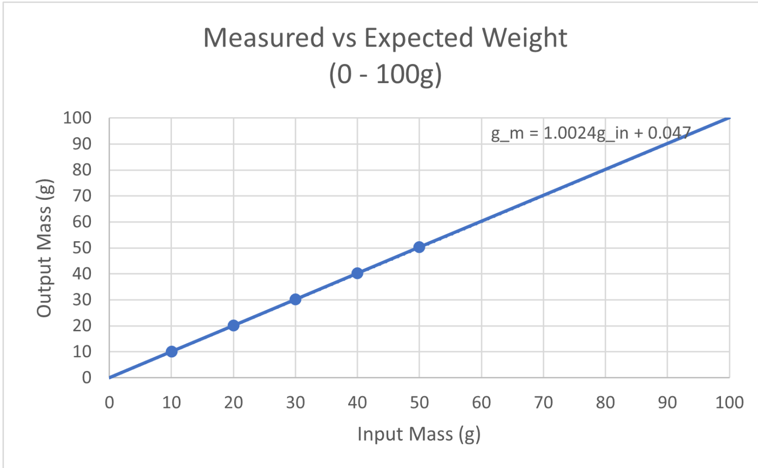

Figure 45: Plot of weight measurements from Table 4.

10.2 Pump

10.2.1 Proof of Concept

The requirement of the pump is to pump water from a small reservoir to the cat bowl. Unlike food intake, cats exhibit extremely high water retention and regulate their water intake precisely. The low water intake allows freedom in determining when and how much water is dispensed. The goal is to dispense up to approximately 3 fluid ounces of water over a duration of three minutes. One fluid ounce of water is approximately 30 mL, or 30 grams, of water. One can freely convert between volume, in mL, and grams of water since the density of water is approximately one. According to the United States Geological Survey, USGS, the maximum deviation in density is 4.3% at 100 degC. Temperatures on the order of 20 to 50 deg C result in an error of approximately 0.5%.

The dispensing of 100 mL, over 3 minutes gives a water flow rate of 90 mL/min. Many low-flow pumps offer flow rates within the hundreds of mL/min to several liters per minute. To test the feasibility of using a low-flow pump to dispense on the order of 10 mL, a 100 mL/minute peristaltic pump was purchased. The pump is incredibly simple, only requiring 12 VDC to operate. The Arduino Nano Every and the load cell from the prior section were used to measure the weight of water dispensed over various duration. The Nano Every does not have a 12V pin, implying that an external DC power supply was needed.

Peristaltic pumps have the benefit of not needing coolant or being submerged in the medium to operate. Before immediately attempting applying 12 V to the pump, the voltage was slowly incremented to determine power draw. The product page stated that the pump required 12 VDC and would draw approximately 80 mA. No further information was provided regarding maximum current draw, peak in-rush current, or peak instantaneous voltage. These three parameters are of concern because the inductive nature of the pump's motor could cause issues with the

V_{in} (V)	3	6	9	12
I_{in} (mA)	180-200	195-215	210 - 230	220-230

Table 13: Pump I-V characteristics

PCB design. The following data was gathered from the DC power supply.

From the I-V characteristics it is clear that it does not match the manufacturer's expectation. Each current was given a range due to the power supply oscillating between the given range. Prior to purchasing the pump, an operating current around 80 mA seemed very low. Interestingly, the input resistance of the pump was measured at 19.6 Ohms. It is aware that the resistance measurement on a DMM is not equivalent to the input impedance but is a ballpark estimate. This is mentioned because an approximate 20 Ohm load with 12 volts across it gives an operating current of 600 mA, much more than what was seen experimentally. Verifying that the pump could work at 12V without drawing substantial current gave us the confidence to begin testing with water.

Firmware Modifications

The load cell was essential in testing due to a volume-marked container being unavailable. At the time of testing, all that was available was an approximate 100 mL, pyrex, petri dish-type container. The firmware from the load cell proof of concept was modified to take continuous measurements. The measurement period was set at 100 ms to provide a fine resolution in measurements. Every 100 ms the measurement was sent over the serial monitor. Additional testing will be necessary with a marked container to verify the volume is accurate.

A threshold variable was set to a target volume. Measurements were only taken while the measured weight was below the threshold weight. The pump will be activated to refill the bowl to a given volume. The standard volume to fill will be determined at a later moment. An initial test with a threshold of 60 mL was chosen to verify the linearity of the pump. The threshold is easily modifiable in the code for longer or shorter duration tests.

Results:

The 60 mL threshold was ran with both a full and empty line. The line refers to the tubing connecting the water reservoir, a gallon jug, to the pump, and from the pump to the dish. The length for each section was 60 cm and 55 cm, respectively. This information is included because the length of the tubing and how full the tubing is will directly affect the time the pump needs to be on. During product fabrication, the length of the tubes will be much shorter. The long length was to allow the water reservoir to be away from sensitive electronics on the bench. The results from the 60 mL threshold with 12V input test is provided below.

The blue plot represents the measured weight when the tubing was full of water. Likewise, the orange plot represents an empty line. A good deal of information can be extracted from this plot. The slope of each plot represents the experimental flow rate of the pump. It was expected that

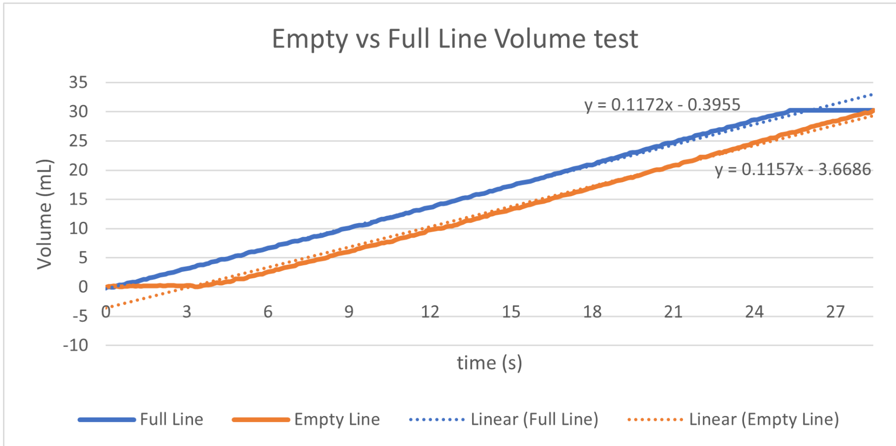

Figure 46: 0 to 60 mL with 12V input measurement plot.

the flow rate be identical and slopes of 117.2 and 115.7 mL per minute confirm these findings. The intercept with the time-axis represents the delay required to fill the line, or the time before water is dispensed into the system.

Such a large focus is placed on the pump characterization because it will directly influence design decisions. A low-flow rate is unable to provide the kinetic energy required to activate a turbine flow sensor. While using the load cell and keeping a running average of the flow rate is not ideal, it provides an approximate reading to verify the amount dispensed. Knowing the flow rate to some accuracy allows the modules to be used in different configurations. One design could involve entirely relying on the load cell to activate the pump. Another design may use the flow sensor and integrate the resultant signal to determine when to stop. The last design could involve using time heuristics. If the pump is assumed to have a flow rate of 100 mL per minute then turning the pump on for 1 minute will give the desired 100 mL. There is an innate error the the last design, however, a simplicity is associated with it. These design decision will be discussed in the Hardware Design Section.

Out of pure curiosity, the input voltage to the pump was varied. It was hypothesized that varying the input voltage will vary the flow rate. A lower input voltage will result in a lower flow rate. The advantage to knowing this information is to provide further hardware design flexibility. Designing the power supply with a 12 V rail purely to run the pump may be wasteful. If the pump could be ran at 5 V for approximately twice the duration it would both increase pump lifetime and hardware complexity. The pump was tested at 3VDC increments, starting at 3VDC. Measuring the volume distribution to a threshold of 60 mL resulted in several minutes long tests. Hence, the threshold was limited to 5 mL. The results of input voltage modulation is provided below.

The line of tubing connected to the pump was full for each test. Waiting for a near meter-long tube to fill with flow rates as low as 20 mL would artificially extend the test. The trendlines for the curves are provided in the table below. Interestingly, there is a linear relation between

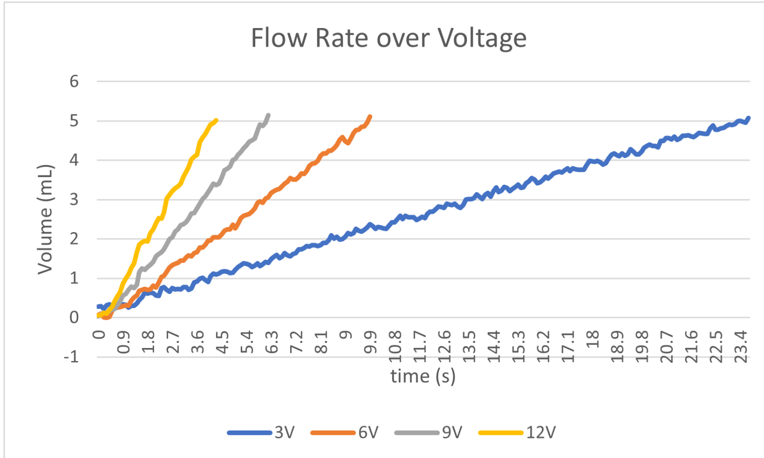

Figure 47: 0 to 5 mL with variable input voltage plot.

$V_{in}(V)$	3	6	9	12
$Q\frac{mL}{min}$	20.7	51.9	84.6	123.6

Table 14: Extrapolated Flow rate over various input voltages.

the measured flow rates. Plotting the data points resulted in the curve, $Q \approx 10V_{in}$. Every volt applied to the input results in a 10 $\frac{mL}{min}$ increase in the flow rate. Note there is a significant error within the 12 V measurement. Inspecting the yellow curve, there is prevalent high-frequency noise, for lack of a better word. The duration of the test was approximately 4 to 5 seconds. Imperfections in the testing setup, such as accidentally touching the load cell, pushing on the table too hard, or accidentally touching the cell with the tubing would introduce significant error. Over a long duration, such as the 3V case any noise would be averaged out; reducing significance.

As mentioned, interest in the flow rate as a function of voltage provides the flexibility of running the pump at a lower voltage or at variable voltages. An interesting stretch goal could be to provide a variable flow rate to satisfy a timing conditions. If the user has cleaned out the bowl, more power should be applied to the pump to fill the bowl sooner. However, filling a third-empty bowl would not require the large input power. These decisions will be discussed in the hardware design chapter.

10.2.2 Inductance Measurement

One concern when switching inductive loads, such as a pump, is the back-emf generated by a sudden change in current. Some pumps include a freewheeling, or flyback diode to reduce the effects of back-emf. However, the purchased pump did not explicitly state whether or not a diode, or some emf reducing mechanism, was included. To guarantee a back-emf does not damage the switching and upstream circuitry it was decided to experimentally measure the pump inductance and calculate the theoretical back-emf.

It is important to note that running a 12 VDC pump operating at approximately 250 mA is likely to have a negligible back-emf. However, the following information is included to allow flexibility in pump choice for individuals recreating this project. The following procedure also demonstrating how an individual could experimentally determine inductance without an LCR meter. At the time of testing, an LCR meter was not available or acquirable. The experiment will provide the complex impedance of the pump; the resistance due to the windings and the inductance of an ideal inductor. Knowing the rough estimate of the complex impedance gives the freedom to replace the pump with a linear model and allow the system to be simulated much easier.

To measure the inductance, a sinusoid with known frequency and amplitude was injected into the pump. The resulting drop in amplitude and induced phase provide sufficient information in calculating the inductance. Three tests were done with a 10 V_{pp} sinusoid at 100 Hz, 1 kHz, and 10 kHz. Three frequencies were chosen because the inductance of a pump should be relatively independent of frequency. Since the pump is not an ideal inductor the winding resistance will be present in the measured impedance. There is also the issue of directly applying a voltage across an inductor and attempting to measure the current. A 100 Ohm resistor, measured to be 98.19 Ohms, was placed in series with the pump. The series resistor is necessary to implicitly measure the current through the pump. Tests were done placing an ammeter in series with the inductor but the series resistor was preferable. Including the series resistance guaranteed the function generator would not be shorted at low frequencies.

The positive terminal of the function generator was attached to the resistor and the negative to the negative of the pump. Oscilloscope probes were attached in parallel with the function generator and across the pump. The ground lead for both probes were attached to the negative of the pump. To those attempting to measure inductance using this technique, be aware of the ground probe. Using a ground-referenced probe to measure the differential voltage across the 100 Ohm resistor will short the motor. With the two ground referenced signals, they could be subtracted to determine the voltage across the resistor. Conveniently, many oscilloscopes feature math channels to operate on various waveforms. One math channel was used to take the voltage difference across the two oscillscope channels and another to divide the difference by 98.19. The resulting waveform represents the current through both the 100 Ohm resistor and the inductor.

With the waveforms for the voltage across the pump and the current through the pump it is possible to determine the impedance. The magnitude of the pump impedance was found through dividing the peak-to-peak voltage across by the peak-to-peak current. The phase between the voltage and current waveforms was found by a separate measurement. Using phasor theory and trigonometry the real and imaginary components of the pump impedance were found. The following table highlights the measured values and resulting impedance over frequency.

Interestingly, the inductance of the pump was not as constant as hoped. It is unsure where such

f (kHz)	V_{Lpp} (V)	$I_{pp}(mA)$	$\|\phi\|$ (deg)	$\|Z\|$ (Ω)	R_p (Ω)	X_L (Ω)	L_p (mH)
0.1	0.8242	67.81	8.33	12.15	12.02	1.760	2.801
1	2.010	66.07	65.0	30.42	12.86	27.57	4.389
10	7.820	38.50	79.7	203.1	36.31	199.8	3.180

Table 15: Pump voltage, current, and impedance measurements over frequency.

variation comes from but it provides the desired estimate of the inductance and series resistance. Therefore the approximate inductance is 3 mH and the series resistance of 12.5 Ohms for the pump. The jump to 36 Ohms in the 10 kHz test is likely an artifact of the pump approaching an open circuit condition at higher frequencies.

10.2.3 Back Emf Calculation

The following calculation intends to describe how necessary a current snubber circuit is to the longevity of the pump and protection of the surrounding circuitry. The standard inductor equation, $V = L\frac{di}{dt}$, may approximate the voltage across the inductor due to a suddent change in current. The rise and fall time of an Arduino's GPIO pins will be used to theoretically switch the pump off. The rise and fall times were measured to be approximately 10 ns, respectively. The purchased Power MOSFET which will switch the pump on and off exhibit a typical switching delay of 35 ns and a fall time of 35.8 ns. In a best case scenario when the GPIO pin controlling the motor is pulled low the current immediately begins to decrease. This is not the case, due to the GPIO fall time and the MOSFET's switching delay but assume these idealities for the calculation. The total time the current will vary is 80.8 ns; the sum of the GPIO delay, switching delay, and the switch fall time. The initial current draw of the pump was measured above to be within 200 mA to 250 mA. Assuming the largest current draw and an inductance of 3 mH. The resultant back emf is on the order of kV; ≈ -9.3 kV.

A back-emf of 9.3 kV is extremely large and would only become larger if the GPIO delay and switching delay are ignored. Practically they would be ignored because the MOSFET is still in conduction and the current will decrease as the device is turning off. The calculation also assumes that the current is being pulsed to zero, which is not necessarily the case. The control voltage modulates the current through the pump meaning that a 10 ns fall time in voltage does not imply a 10 ns fall time in current. There are other practical issues like spark gaps which would prevent extremely large voltages from being realized. The distances between traces, or across the terminals of the pump, would be prime suspects for a spark gap to form and force the current draw necessary.

While an alarming issue, it seems that either the purchased pump has an emf suppression mechanism or an error has been made in the calculation. Preliminary tests applying a 5 VDC pulse with 10 ns tise and fall times to the pump produces a maximum back emf of approximately 5 V. The function generator was ran in high-impedance mode so further testing is necessary with the switching circuit to better approximate the back-emf. Regardless of the follow-up test a snubber will be included in the design to ensure an edge case is never encountered.

10.3 Motor

The intent of this segment is to illustrate to the reader known standards for testing stepper motors used in the manner described in this document. The scope in which these tests are administered, follow the IEEE standards of IEEE 112-2017 - IEEE Standard Test Procedure for Polyphase Induction Motors and Generators. The bulk of the documentation includes different methodologies for a variety of different types of induction motors and generators. Since, the Purrfect Cat Care system involves the stepper motor to perform motor like functionalities only tests and calculations for motor testing will be recognized in this segment.

In order for the stepper motor to yield the most usefulness to the design, calibration and testing should be performed to ensure that the motor receives enough power to the stators to rotate the rotor, to ensure losses across the stators and the rotor are at a minimum, and both Slip loss & Core loss are also accounted for. This segment for testing is broken up into two parts, types of losses and the associated calculations and what they mean followed by the types of tests that will be conducted to ensure optimum operation of the motor. This segment does not cover all elements of testing as offered by the IEEE 112-2017 document, instead only offers relevant test for losses, efficiency tests, and performance as it relates to the chosen induction style motor.

Stator Power loss is of some interest since the efficient use of the motor must use adequate power as to not overheat the inductive coils which would result in mismanagement of power. Dr. Al-Zubaidi of Al-Mustansiriyah University Baghdad, mentions there are two categories of losses to consider. The first is fixed loses. This may be attributed to how the inductive motor is designed, which may include but not limited to mechanical friction or magnetic core losses. The second mentioned includes variable losses, which includes the effects of increased load on the shaft of the motor, which increases the drawn current. Power as a result may be lost across the windings of the Stators in the form of what is called copper losses. Based on these concerns, the following power equation models that of a three-phase motor ”by where I is the measured or calculated current per terminal measured in amperes A, R is the DC resistance measured in (Ω) between any two terminals, and R_1 is the per phase DC resistance”.

$$P_{SIR} = 1.5I^2R = 3I^2R_1 \ (1) \tag{2}$$

The above definition is used in relationships used throughout the this segment to determine quantities like core and rotor loss. Rotor Power loss falls into the same category of fixed loss and modelled as:

$$P_{\text{RLoss}} = (\text{measured stator input power} - P_{SIR}) \times slip \tag{3}$$

Slip describes the ratio of slip speed and synchronous speed and is a dimensionless unit since slip speed and synchronous speed are measured in units of revolutions per minute. This quantity represents the speed at which the magnetic field produced by the stators rotate around the cylindrical housing with respect to the speed at which the rotor is attracted to the change in position of this magnetic field. It is this lagging of the rotor with respect to the stator magnetic field lines that create what is considered useful torque. Slip is then modelled by the equation:

$$s = \frac{\text{slip speed}\,({}^{r}\!/\!{}_{min})}{\text{synchronous speed}\,({}^{r}\!/\!{}_{min})} \text{ , where , slip speed} = n_s + n_r \text{ , } n_s = 120 \times \frac{f}{p} \text{ ,} \tag{4}$$

Where, n_s = synchronous speed, n_r = measured speed of the rotor, f = frequency and p = poles. A No-load test should be performed in order to determine a baseline at which the motor operates. To perform this test, the motor should be ran at the rated voltage and frequency should be measured with no load attached. The measurement of the temperature, voltage, current, and power input starting at 125% of the rated voltage should be taken until the reduction in voltage increases the current. The measured input power is the total loss in the motor with no load. These losses include P_{SIR}, friction, windage, and core losses. The friction and windage losses may be determined through the use of linear regression analysis. This can be calculated by taking three or more data points of the power versus the voltage square curve. Determination of the friction and windage loss is the difference between the stator power loss and the total losses at each test voltage point. This may be translated into a power versus voltage curve that terminates at 0V. The intercept of power at 0V describes the friction and windage loss. Equivalently, the difference of the input power and the stator power loss plotted against the voltage squared for values in lower voltage ranges may also be performed.

Highlighted within the Load test section of the IEEE Std 112-2017, covers prescribed literature for efficiency test methods used to determine efficiency of induction motor directly, or indirectly using stray-load loss using either Efficiency Test Method A or B/B1/C. As suggested, a load is attached to the motor and is subjected to four different loads at 25%, 50%, 75%, and 100% of load capacity followed by two overload measurements between 100% and 150% max load. These data points should be used in conjunction with Test Method A or B/B1/C and should be evenly load values in order to get an adequate spread for the load range. A mention of stator winding resistance for the mentioned load capacities should be measured and estimated by comparing measured temperature with temperature measurements made at steady-state. Types of thermal measurement devices include an embedded temperature detector, a temp sensor positioned on the stator coil end, or an air outlet temp sensor. It is lastly suggested that each measurement should be obtained at each load capacity value and should measure in descending order. Suggested readings should include electrical power, current, voltage, frequency, speed, slip, torque, stator winding temp or resistance, and ambient temp.

As mentioned earlier, stray-load loss is a measurement that results when all the know values of stator power loss, rotor power loss, core loss, friction and windage are accounted for. The sum of these losses will not always equal 100% , instead the remaining value is assigned the stray-load loss label. There are two different approaches that may be used when determining this type of loss, direct and indirect measurements. The description mentioned is an indirect approach to obtaining this value, however Efficiency Test Methods E, F, and E/F are used to measure for it directly. This may be necessary because the losses mentioned may not always correlate with the same category of measurements. Yamazaki and Haruishi mention that these losses fall into mechanical loss, primary copper loss, secondary copper loss, iron loss, and stray-load loss. They further mention the categories of losses may not always satisfy these relations like the measurements required to obtain iron loss, which also involve precursory tests in order to determine value. The exact physics of why this is important will not be explored here, rather mentioned to explain its relationship to increased harmonic losses due to load.

In the IEEE Std. 112-2017, a brief description of how harmonics cause loss is calculated when stray-load loss occurs at the fundamental frequency by applying balanced mult-phase voltage to the stator winding terminals in the absence of the rotor. It is explained that the electrical input minus the stator power loss at test temperature is equal to the fundamental frequency stray-load loss. While performing this test, it should be noted that the structural components, like bearing brackets, should remain in place as they contribute to the overall stray-load loss. The currents that are involved in this test are described as $I_t = \sqrt{I^2 - {I_0}^2}$, I_t describes the value of the stator winding while I_0 describes the same value at no-load current (A). These values may be used in the appropriate test methods mentioned earlier, however, must correspond with the appropriate load ranges of 25%-150% of max load. To measure values for I_t, the applied voltage should be varied for optimal current values, then record input power, current, and winding temperature.

In order to calculate Stray-load loss, a measurement of stray-load loss at high frequency should be performed. According to the testing procedure, stray-load loss occurring at high frequencies should be measured when the rotation is operated in reverse rotation. To perform this test, the motor should be completely assembled at this point and a polyphase input should be applied at the rated motor frequency to the stator winding terminals. When this happens, it is explained that the rotor is being driven by external means at approximately synchronous speeds. This influences the rotor to rotate in the opposite direction to the rotation of the stator magnetic field. Once achieved, the value of the input should be measured to correspond with this characteristic. As a caveat to this test method, it is advised that overheating may be an issue for motors with unidirectional cooling systems. The recommendation follows that the motor should be driven by external means at synchronous speed in the normal direction as it pertains to the specific motor. This enables the appropriate ventilation, however the power connections to the stator terminals should be reversed in order to generate the stator magnetic field to rotate in the opposing direction.

Mechanical power should be measured by driving the motor with and without current to the stator winding. During the current application test, current should be measured as done in the previous test for fundamental frequency and high frequency measurements. In situations with and without current applied to the stator windings, the current should be the same. If the motor is a wound-rotor motor, the rotor terminals should be short-circuited. Measurements of the current should be made to determine the mechanical power to drive the motor, input power, and winding temperature. Additionally, mechanical power should be measured at a zero input current.

The stray-load loss calculations are made via the following equations and definitions as stated in the IEEE Std 112-2017. $P_{SL} = P_{SLs} + P_{SLr}$ The following definitions represent the components of this equation for stray-load loss in units of watts.

$$P_{SLs} = \text{fundamental frequency stray-load loss} = P_S - P_{SIR} \cdot P_{SLr} \tag{5}$$

$$P_{SLr} = \text{High frequency stray-load loss} = (P_r - P_m) - (P_{rr} - P_{SLs} - P_{SIR}) \tag{6}$$

Where P_m equals the mechanical power, or the power required to drive the rotor in the absence of applied voltage to stators. P_r is the mechanical power, power required to drive rotor in the presence of applied voltage to stators. P_{rr} is the applied input voltage to stators during reverse-rotation test. P_s is the electrical input to stators when the rotor is removed.

It is suggested that in order to see the raw data smoothed out, the relationship between P_r and P_m as well as P_s and P_{rr} should require a series of three regression analysis to be performed. This will clean up unnecessary data points that may have no impact on the overall system. The regression analysis should conform to the $log\,(test\ power)$ versus $log\,(test\ current)$. The following equations may be used to plot these respective curves in order to determine the accuracy of measurements.

$$P_r - P_m = A_1\,(I_t)^{N_1} \tag{7}$$

$$P_s = A_2\,(I_t)^{N_2} \tag{8}$$

$$P_{rr} = A_3\,(I_t)^{N_3} \tag{9}$$

A_N is the y-intercept on log-log plot (constant) N_i is the slope on the log-log plot ≈ 2 I_t is the measurement taken for the current during the stray-loss test (A) $i = 1, 2, 3$ As a side note, the data will be accurate if each curve adheres to the square-law relationship between power and current.

The last topic for loss is power factor, which is an independent calculation that yields information about the motor performance characteristics. According to Fluke corporation, “power factor is an expression of energy efficiency”. Often times this can be expressed in terms of percentage where 100% indicates max efficiency. It is described that this is the ratio of working power (kW) and apparent power (kVA). Fluke continues to describe the components of apparent power as a demand component for the system. It is a measured quantity that allows for nominal operation of a system per unit time. They explain the components of Power factor by using an analogy using a mug of beer. In this comparison, the mug represents apparent power, which is what is being delivered to the system and the foam and liquid beer represents the wasted power and useful power respectively.

As stated in the IEEE Std. 112-2017 document, Power factor may be measured indirectly by measuring the machine electrical power labelled P, the measurement of the input as the line-to-line voltage labelled V, the input current labelled I, and is equated to power factor labelled PF as shown:

$$PF = \frac{P}{\sqrt{3} \times VI} \tag{10}$$

10.3.1 Safety Concerns

This section visits the content that reflects on the safety parameters around electric, magnetic, and electromagnetic fields. The general source of reference for this segment calls upon IEEE Std. C95.1-2019. This is a standard that defines the limits of exposure in the presence of induction motors and generators operating in the frequencies between 0Hz and 300GHz. Based on the purpose of the stepper motor, rotating a simple axle, the frequency operation should only include frequencies between 0Hz-1kHz. Furthermore, insight into the range of frequencies as it pertains to thermal radiation, which ranges between 100kHz to 300GHz, will not be considered. As a result, discussions within the scope of the IEEE Std. C95.1-2019 will encompass the electrostimulation effects between 0-5MHz.

IEEE Std. C95.1 discusses, two types of reference values that define safe exposure limit while operating on induction style motors, Dosimetric reference limit (DRL) and Exposure reference level (ERL). DRL acts as the absolute max an individual may endure before sustaining adverse effects as it relates to electrostimulation, in contrast, ERLs are a local max that generalizes a range at which exposure is tolerated. For context, DRLs was referenced to discusses at what value the electric field needs to be to stimulate muscle contractions. Two frequencies were given, one of which explains, at a frequency of 20Hz, the electric field strength on the human brain is in the realm of 5.89 $^{mV}/_{m}$, for persons in unrestricted environments and 17.7 $^{mV}/_{m}$ for persons who were allowed in restricted environments. In the neighborhood of 167Hz the heart may be present in electric field strengths of 943 $^{mV}/_{m}$ for both respective categories. The ranges in which the ERLs are described, 0-20Hz (118mT to (18.1/f)mT, are allowable limits in which a person may be present when the magnetic flux density and magnetic fields for a duration of less than 1 second respectively.

Given these values, it is important to understand that for a time-varying magnetic field, the energy between coils of wire that happen to be magnetically coupled with another system, the distance for coupling, is less than a meter. The energy attributed to the electric field is even less and may be modelled by the inverse-square law. The values described in the standards of IEEE, model cases in which a person were subjected such radiations, these are the intensities which they may remain unaffected to minimal harm. Much of the discussion as it pertains to electric field radiation revolve around higher frequencies, typically 100kHz-110MHz, and align with far-field exposures, greater than several meters. Since normal operation requires no direct contact with the stepper motor, further discussion is not needed.

This segment covers the standard IEEE Std C37.96-2012. These are recommended practices for the preservation of induction style motors and offer an array of different practicing methods to prolong the life of these motors as well as to guides to incorporate components to aid in this endeavor. Although the guide is used for the purpose of three-phase horsepower motors the information provided does include enough guidance and common practice for general protection in most applications of induction style motors.

Since the stepper motor will operate in a manner that rotates an axle to transfer a load along the length of a connected arm, constant torque must be applied. If not observed, the induction motor may be prone to stalling. This happens when the load torque exceeds the breakdown torque, in other words the effort of the system struggling to overcome the load's tendency to remain at rest. This is a byproduct of the motor not being supplied with adequate power.

Additionally, for synchronous motors, a motor may tend to lose synchronism with respect to the system, known as being "out-of-step". This shares a common problem with motor stalling which is the result of a load capacity that requires greater torque than can be supplied, voltage supply reduction is too great, and motor excitation is too low. It is suggested that out-of-step detection devices be used for synchronous motors to monitor the stator power-factor angle. Other types of devices may include a device that senses alternating current within the rotor circuit or impedance-type to determine when the motor transient reactance exceeds the system impedance at the motor terminals.

General-purpose alternating-current polyphase 60Hz induction motors with 2, 4, 6, and 8 pole designs are not meant to be operated at the their rating on a 50Hz circuit. Mike Leibowitz, of National Electric Manufacturers Association (NEMA), states in an ANS document NEMA MG 1-2016 that voltage should be appropriately adjusted to compensate the lower frequency. He states that applied voltage and horsepower should be set at 5/6 of the voltage and horsepower rating of the motor respectively when running at 50Hz. It is further stated that speed and slip will operate at 5/6th of the speed and slip at 60Hz, Locked-Rotor current will yield a 5% decrease, but Torque remains relatively the same.

When line voltages appear to be unbalanced at the terminals of the motor, this could create defining and damaging problems for the motor in the long term. A small percentage difference in the line voltages could cascade into larger current unbalance. This could result in further damage by heating up the coils of the stators. It is highly recommended that motors maintain balanced line voltages in order to avoid such behaviors. If incurring voltage imbalances remains unavoidable, it is recommended to install overload devices to handle the overload characteristics of current being at max peak. The importance of this on the performance of the motor ends up hindering the procession of the rotor by creating voltage imbalances at the terminals of the stators and in turn randomly delaying the execution of each step. Additional considerations entail performance in the realm of adequate torque and full-load speed suffer a percentage based on the severity of the voltage imbalance.

10.3.2 Inductance Measurement

Refer to the pump inductance measurement for the experimental setup to measure motor inductance as much of the section will be similar. As mentioned, knowing the impedance is pivotal in designing proper protection circuitry. A stepper driver will coordinate applying power to each phase and typically offer back emf protection. However, knowing the theoretical back emf will allow the design the freedom to be used with other motor types and confirm that the chosen driver's protection is sufficient.

The chosen hybrid stepper motor utilizes a bipolar phase configuration. As mentioned, the two phase are controlled independently by the driver but are symmetric in operation. Hence, measuring the inductance of one phase should be similar to the alternate phase. It is important to note that the two phases are magnetically coupled. Refer to the Sec 3.1 for additional information on bipolar construction and theory of operation. This is important to note that the inductance of one phase is not purely the inductance measured between the two sense wires. A voltage will be developed across the alternate phase in response to this coupling. The coupling will be ignored as the mutual inductance is a function of $\sqrt{L_a L_b}$ for two inductors in parallel. Calculating the inductance of a single phase will overestimate the inductance, providing more headroom with the protection calculation.

A 100 Ohm resistor, measured to be 98.74 Ohms, was placed in series with phase B of the motor. The function generator was attached with the positive terminal on the resistor and the negative on the negative channel line. Oscilloscope probes were places at the positive sense line and at the positive terminal of the function generator. The ground leads for both channels were attached to ground. A third channel was attached to the positive and negative channel lines for phase A. The third channeled measured the induced voltage of phase A in response to phase B. The following measurements were taken:

f (kHz)	V_{Lpp} (V)	$I_{pp}(mA)$	$\lvert\phi\rvert$ (deg)	$\lvert Z\rvert$ (Ω)	R_p (Ω)	X_L (Ω)	L_p (mH)	$V_{ind,pp}$ (mV)
0.1	1.027	66.53	23.31	15.44	14.18	6.109	9.724	300
1	3.450	62.61	75.13	55.10	14.14	53.25	8.476	25
10	9.091	23.32	82.41	390.1	51.59	386.7	6.154	≈ 0

Table 16: Motor voltage, current, and impedance measurement over frequency.

Interestingly the motor inductance decreased with frequency. The theory behind this decrease is unknown and could prompt additional testing. However, the experimental maximum of approximately 10 mH is sufficient in determining the back-emf.

10.3.3 Back Emf Calculation

Lin engineering graciously has a torque-speed curve plotter on their website. The motor is intended to run at 24 VDC with 600 mA current draw but this is not a hard requirement. Additional testing is needed to determine an accurate torque to dispense the food in a timely manner. Operating the motor at 12 VDC with 250 mA current draw could be a viable option. Operating the motor outside of the 24 V, 600 mA, will change the back emf generated. Regardless, the worst case scenario involves switching off 600 mA over a 80.8 ns duration. The resultant emf is approximately 74 kV. The ionization voltage for air is about 30 kV per cm, implying that a spark is likely to form either on the sense wires or internally in the motor. Therefore, an emf supression circuity is likely unnecessary but included regardless.

10.3.4 Initial Testing:

To better understand how the phasis of the Lin Engineering hybrid stepper motor behave, the function generator was used to provide a signal to each of the four phases. Several tests were done with various generator settings such as high impedance, equivalent output impedance, and varying the phase of each channel. The goal was to note any observations which may simplify the signal generation for the stepper motor.

The Tektronix AFG30xx line was available in the lab and features two independent channels. The two channels were set to high impedance to verify each phase would not accidentally short the generator. A 5 V square wave centered at 2.5 V and with a frequency of 60 Hz was set on channels. The phase of the second channel was offset 180 degrees with respect to channel one. The two signals were attached to the A and B phase directly and the signals were activated. The phase was varied to determine which configuration produced the highest torque; qualitatively. Initial findings reported that a 180 degree phase shift was preferred, however, the torque was lackluster.

To improve the torque, it was decided to change the impedance of each channel to match the equivalent series resistance of the phase. Mentioned in the datasheet, the stepper motor exhibits 10 Ω per phase. Setting the load impedance on the generator to 10 Ohms reduced the maximum voltage of the square wave to 3.3 V. One would expect that operating the motor at 3.3 V would not be sufficient, the motor was able to turn. It is believed that the impedance matching results in a greater net power being delivered to the phase then compared to the high impedance tests. It is important to reiterate that the final design does not generate the signals manually, the A4988 stepper driver IC handles the signal generation. These tests were done at a time where a different stepper driver was used which featured a PWM input array to control each phase. Since this testing was essential in understanding the physics of the hybrid stepper motor, it was deemed sufficient to remain in the document.

10.4 Proximity Sensor

10.4.1 Proof of Concept

The prototyping of the proximity sensor was an incredibly simple process. Throughout the design, a 555 time operating as an astable oscillator was constructed on a breadboard. However, to simplify the initial setup a function generator was used to produce the 38 kHz square wave. As mention in the Chapter 8, the transmitter requires only a series resistor and an IR diode. The receiver only required a connection to a 3.3 V power supply and an oscilloscope probe was place on the output signal pin.

A visualization of the proximity prototyping is present in the final demonstration video. Throughout testing a meter stick was used to measure the distance between the transmitter and receiver. Under the operating conditions presented in Chapter 8 the transciever was able to create an optical beam along the meter stick and correctly provided output pulses on detection.

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11 Software & Firmware Verification

Verification of the software components is necessary to ensure that the system is working. Software engineering is unlike other forms of engineering in that the systems are built incrementally, and are in some cases ”designed as we go,” rather than following a monolithic design from the start. To this end, testing is crucial throughout the lifespan of the software to ensure that additions, fixes, and modifications do not come at the detriment of existing functionality.

11.1 Testing

Verifying software components is primarily done through testing. As the software is developed, a testing procedure that ensures the system meets the requirements specifications will also be developed. To thoroughly test the software, a heirarchy of tests is required that validates each level of the software, from individual functions and objects to the entire system as a whole.

To properly test, a testing stack consisting of unit tests, integration tests, system tests, and acceptance tests will be used. Additionally, there will be a combination of manual and automatic testing done to get full coverage of every component and system.

11.2 Unit Testing

Unit testing, or component testing, is defined by BS-7925 as the testing of individual software components. Specifically, it is performed to verify the functionality of each individual component in the software system by ensuring that with the correct setup and input, the correct output is provided. It operates on ”units” such as functions, objects, and methods.

Unit testing covers these areas:

1. Conditions inside and outside the range of valid input, for each variable in a function.
2. Each possible logic branch in a function.
3. Each calculation that affects the output of the function.

11.2.1 Unit Testing Libraries

A number of libraries exist for different languages to implement unit tests. For C++, two popular libraries are Catch2 and GoogleTest. Both libraries are simple to implement and allow writing tests in a narrative structure. Catch2 in particular is a header-only library that is easy to integrate into any C++ project, so it will be used for the device server.

For backend testing on Node.js, Mocha is a popular testing library and Chai provides a library of asserts that works very well with it. Mocha and Chai will be used together to test the API endpoints.

For frontend testing, Jasmine, a testing library for JavaScript, and Karma, a tool that allows tests to be run outside of the main server by spawning an independent HTTP server will be used.

11.3 Integration Testing

Above unit testing is Integration testing, defined by BS-7925 as ”The process of testing an integrated system to verify that it meets specified requirements.” Since this project has many parts that will be under development at the same time, stubs and drivers will need to be developed to perform certain tests. Stubs and drivers are programs that stand in for the real, unfinished program, so that the parts under test can operate correctly. Stubs stand in for called programs, while drivers stand in for calling programs.

An incremental integration testing model will be used, whereby related components are connected to each other and then tested. Once they are working sufficiently, another component can then be connected. This process is continued until the entire system has been integrated and all components are tested and working with each other.

11.4 System Testing

Once individual components are integrated into a complete system, system testing can be done. System testing is defined by BS-7925 as ”The process of testing an integrated system to verify that it meets specified requirements.”

System Testing is a form of ”black box” testing, in which the internal components are no longer being tested, because the focus is on the external usage of the system. The system as a whole is evaluated to ensure that it works correctly and meets requirements.

11.5 Acceptance Testing

Acceptance testing is defined by BS-7925 as ”Formal testing conducted to enable a user, customer, or other authorized entity to determine whether to accept a system or component.” Acceptance testing is done to ensure that the software meets the given requirements, and it is done at a higher level than system testing, which focuses on the technical correctness of the system.

Acceptance testing focuses on the inputs generated by the user, and the output generated by the software as a result. Acceptance testing can involve manual test procedures, or automated testing.

Acceptance testing also focuses on the user experience, and whether or not the system actually meets the user's needs. For this project, acceptance testing will involve determining if the software actually supports the requirements of the project as a whole, and if not, what needs to be done to fix it.

Acceptance testing covers these areas:

1. The whole range of possible input, including valid and invalid inputs.
2. The output generated when valid input is provided, and ensuring that it is correct output.
3. The output generated when invalid input is provided, and ensuring that it is handled appropriately.

To test the API, Postman allowed the endpoints to be tested using a test environment where each endpoint is called to test it's functionality.

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12 Product Fabrication

Several mechanical components are necessary in the feeding and water stations. A mechanism to dispense food into the bowl, to house the food, and to house the water must be either designed or purchased. Purchasing each of the components may restrict the size of the design, hence manufacturing techniques such as 3D printing will be used to facilitate rapid prototyping. This chapter also includes notes on PCB design.

12.1 Screw Dispenser

One of the most important components in the food station is the type of dispenser which is suitable to dispense an appropriate amount of food. The dispenser is the bottle neck restricting the rate of dry food may flow from the capacity tank to the bowl. The dispenser must also deal with the possibility of food jamming the mechanism. When a feeder stops the flow of the food should cease almost instantaneously. When the feeder is turned on, there should be a close relationship between the pace at which it operates and the rate at which the majority of the food is dispensed. Volumetric and gravimetric feeders are the two most common type. The volumetric feeder adjusts and controls the rate of volumetric outflow from the capacity tank. The screw, belt and rotary valve are the most frequent style of feeders. The mass flow rate of a gravimetric feeder is modulated by varying the mass per unit time or by discharging a certain mass of dry food and then turning off the feeder. The two most common types of gravimetric feeders are loss-in-weight and weight belt. Gravimetric feeders should be used whenever there is a requirement for close control of material discharge and when bulk density of material varies. Some of the criteria for feeder selection should include:

- Reliable and uninterrupted flow of material from capacity tank.
- The desire degree of control of discharge rate over the necessary range no longer then 12 inches.
- Uniform withdrawal of material through the outlet of the upstream device
- I Interface with the upstream device in such a way that the loads acting on the feeder from the upstream device are minimal, reducing the power required to run the feeder, particle attrition, and abrasive wear of the feeder components.

The food system cannot be implemented using a gravimetric feeder since the system will be automated. Thus, a volumetric feeder has the adequate technology necessary to adjust and control the rate of the outflow from the capacity tank. The feeding system would operate in a manner similar to the volumetric feeder, except that instead of dispensing the food after it has been weighed, the food would be measured by a load cell after it has been dispensed. The user will predetermine a threshold that will dictate the amount of food dispensed. A stepper motor would be used to control this system. Controlling the current that flows through stepper motor inductors, which provide a magnetic field force, as previously mentioned, to align the rotor. Thus, precisely aligning the rotor based on the current flow regarding another active phase. These strategies improve the angle at which the steps occur and the number of steps per active phase pair. Hence, number of steps are required to increase the torque grade. The amount of torque required is determined by the hopper size and slot outlets. [91]

The need to provide a safety factor above the critical arching dimension to accommodate variations in the bulk material or operating circumstances is one of the primary reasons why hopper outlet sizes are invariably larger than those required to generate reliable flow and pass the required rate of discharge. For improved flow generation, and storage capacity, the hopper portion can transition into a slot outlet; resulting in a local plane channel flow. The force operating on the feeder and the motor are proportional to the power requirements due to pressure on the hopper outlet. Because the impact is significant on big installations, the larger the outlet, the larger the potential force that may act through it. Wider openings cause the failing arch to transmit additional overpressure from the superimposed material; hence a crucial factor that determines the load acting on a feeder is by how much the opening size exceeds the critical arching dimension. The force acting through the outlet from material under the failing arch will still be a function of the parabolic volume of an arch. This component of the feeder loading increases as the square of the outlet width on a plane flow hopper.[91]

In order to mitigate the above problem, it is recommended to design and construct a hopper outlet with from the following guidelines:

- Design the mass flow for maximum effectiveness of outlet size and minimize load.
- Outlet length/width ratio should exceed 3:1 to secure full benefit of plane flow.
- Consider fitting a minor flow obstruction or slide gate that can be with ran withdrawn starting the extraction.
- Ensure feeder offers progressive extraction capability to avoid shearing against stationary layer of material.
- Avoid widening hopper outlet as this will increase load, instead increase depth of extraction for feeder.
- An efficient interface design must include not only incremental extraction along the length of the outlet slot from a hopper, but also continuous dilatation of the bulk solid in the change of flow direction at the hopper outlet. For example, granular materials require more dilation to allow relative motion of the larger particles and avoid jamming at the final exit point from the hopper.

The qualities of the bulk material being handled, and the application are the most important factors in determining which type of feeder to utilize. The tables below show which of four typical types of feeders is best suited to each of these applications.

Variable	Screw	Belt	Valve	Vibrating Pan
Max. Particle Size	μm to 1/3 of minimum pitch	6 in	1/2 in	12 in & large
Particles degrade easily	fair	good	fair	good
Dry powder material	good	fair	excellent	poor
Overpressure sensitivity	fair	good	fair	poor

Table 17: Feeder selection material consideration.

There are three basic types of KWS screw feeder:

- Variable or Stepped Pitch: As the screw advances toward the screw feeder's discharge, the pitch of the screw increases from shorter to longer. With variable pitch, each pitch increases in length in the intake portion, resulting in increasing accessible volume for bulk material addition from the hopper. The flight pitch adjusts in increments with stepped pitch. In the intake segment of a stepped pitch screw feeder, for example, there may be 2-feet of 1/3 pitch followed by 2-feet of 2/3 pitch.
- Tapered Outside Diameter: The screw's outer diameter tapers from the rear of the intake aperture to the shroud, providing more accessible space for bulk material addition from the hopper.
- Mass Flow: Jenike and Johanson created the mass flow design, which is a mix of variable pitch and tapered interior diameter. From the back of the inlet aperture to the center of the inlet opening, a tapering cone is situated on the screw's center pipe. Short pitch flights are installed on the cone, allowing for the insertion of bulk materials from the hopper. The screw is then fitted with variable pitch, beginning where the cone terminates and continuing until the discharge.[23]

As shown in the figure above, screw feeders are well suited for use with bins having elongated outlets. These feeders have an advantage over belt in that there is no return element to spill solids. Since a screw is totally enclosed, it is excellent for use with fine, dusty materials. This advantage would be useful to keep food free from dust. In addition, its fewer moving parts mean that it requires less militance then a belt feeder. The key to effective screw feeder design is to enhance capacity in the feed direction. This is especially true when the screw is utilized beneath a hopper with an expanded output. As a result, the team chose a predesign for the food feeder that incorporates a hopper with a mass flow design that ensures smooth flow.[130] The image below is a publicly available 3D model for a feeder screw. The screw is 3D printed alongside a cylindrical housing for initial prototyping.

Variable	Screw	Belt	Rotary Valve	Vibrating Pan
Direct Impact Tolerance	fair	poor	poor	good
Hopper Outlet Configuration	square, round, or rectangular	square, round, or rectangular,	square or round	square or round
Operation Type	volumetric	either	volumetric	volumetric
Gas Pressure Insulation	poor	N/A	good	N/A
Return Spillage	None	very poor	none	none
Dust Control	good	poor	good	good (enclosed only)
Cleanout Ease	good (quick assembly)	good	good (quick assembly)	good
Tramp Metal Tolerance	fair	good	poor	good

Table 18: Application specific feeders selection.

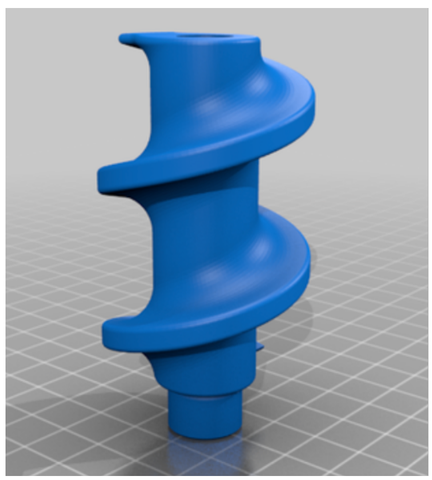

Figure 48: 3D printed screw model.

12.2 PCB Design

Due to the scale of the project the a PCB was designed only for the food and water stations. It was the team's hope to create a PCB for the all three stations. The decision was made to exclude the waste station due to the stations simplicity. Each station has been broken into two boards, a digital and power board. The power board was separated from the digital board to reduce complexity with the PCB and allow the boards to be designed independently. In addition, the separate boards may be reduced to a 2-layer board. Attempting to integrate the two boards would likely benefit from a 4-layer design. None of the team members has designed, fabricated, and verified a PCB prior to this project, hence, streamlining the process was preferable. The following subsections will present the finalized PCB layout for stations and the power board.

12.2.1 Water Station

The finalized water station layout is provided in the figure below.

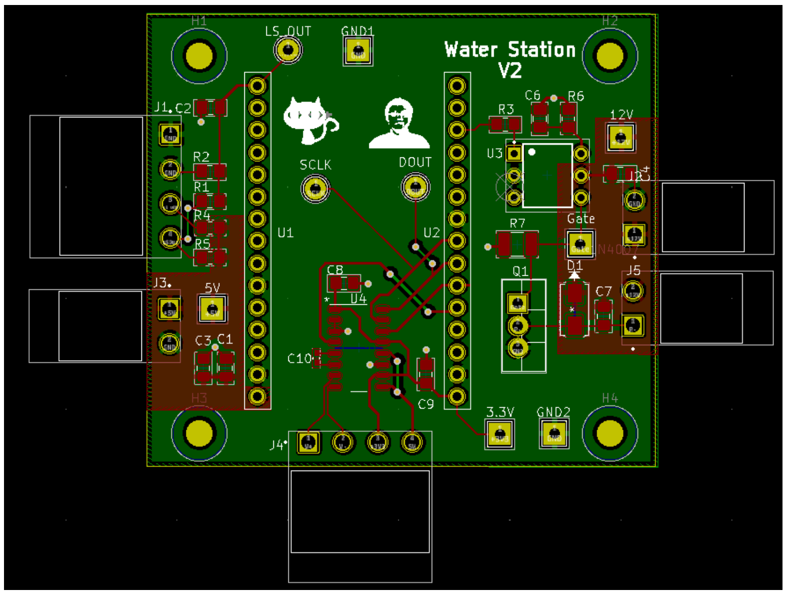

Figure 49: Finalized water station PCB layout.

The layout above is broken into several sections. The most distinguished sections are the 5 V and 12 V domains denoted by the red copper pours. The 5 V section is on the left side of the figure and the 12 V section is to the right. Above the 5 V plane is the level sensor interface. The supporting passives have been placed in close proximity to the ADC pin on the ESP. Within the header pins of the ESP lies the ADS1231 and the chip's supporting passives. In the first revision, the ADS1231 was placed outside of the header pins. A significant motivation for the revision was due to space optimizations such as moving components within the headers and further separating the 5 and 12 V domains.

Moving onto the 12 V section, the top-most section includes the optocoupler and bypass capacitors for the power plane. The Pump drive circuitry is present below the optocoupler from the R7 resistor downwards. Other noteworthy design choicers were the inclusion of many test points. Nearly every important node in the circuit has an associated test point which allow for measurements to be taken conveniently. The SCLK and DOUT signals will be placed underneath the ESP. It was acknowledged that there would be little space to fit an oscilloscope probe underneath the ESP. Hence, the testpoints were chosen so debug wires could be soldered and the signal routed to a more convenient location.

The use of connectors was a design choice made early throughout the PCB layout. The team had seen several other senior design teams with a rats nest of wires soldered to their board. The team wanted to be more organized, and allow various sensors or subsystems be disconnected. The disconnection also allowed for a more positive integration stage. Each subsystem could be tested with the PCB individually and sets of subsystems could be paired and verified together.

The final size of the board came out to 2.3 inches by 2.0 inches. Only two layers were necessary with the top layer including signal and various power planes. The bottom layer, in green, composes a ground plane. Kicad was used to design the PCB and the software includes a 3D viewer. The 3D view for the waster station PCB is provided in the figure below. Note, many of the common passives and the N-channel MOSFET do not have a 3D model. The Kicad project was created in Kicad 5.0 and version 6.0 was released midway through development. It is unsure if it is a bug with project conversion, but the solder pads represent the relative sizes sufficiently.

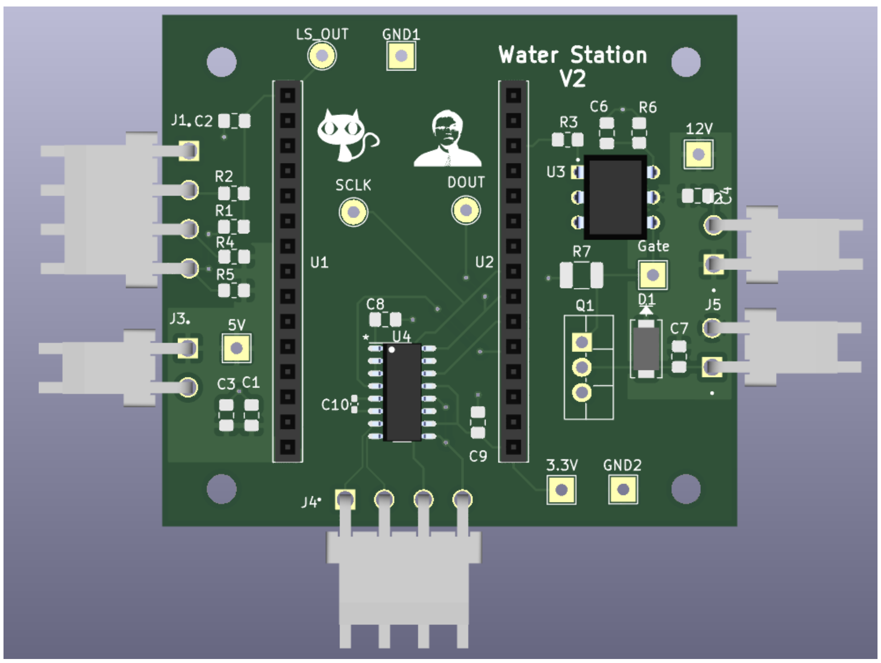

Figure 50: Finalized water station PCB 3D render.

12.2.2 Food Station

The finalized food station PCB layout is provided in the figure below.

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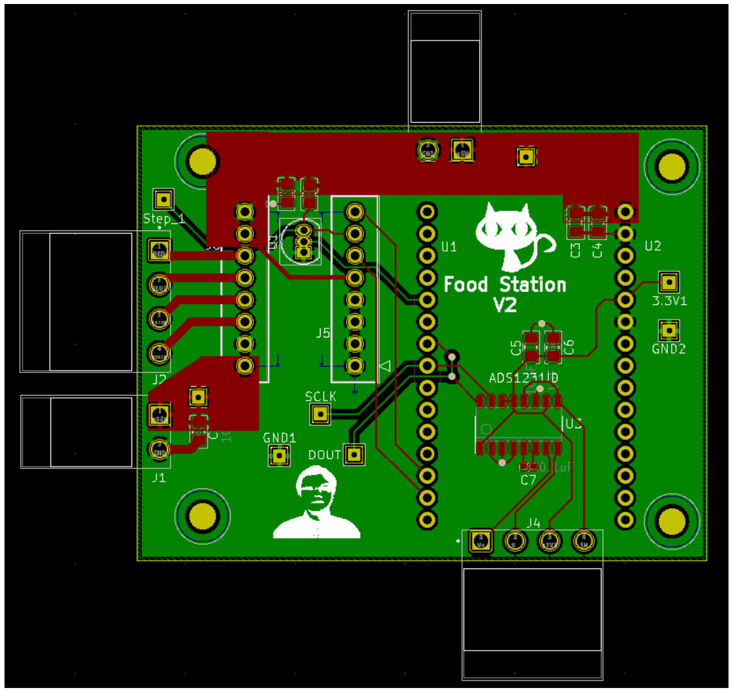

Figure 51: Finalized food station PCB layout.

Much of the same design guidelines for the water station were followed with the food station. Beginning with the ESP in the right-most side of the figure, the ADS1231 is present with relevant passives were placed under the ESP. Slightly above the ESP is a large copper pour representing the 5 V power plane. The two rows of header pins to the left of the ESP represent the socket for the A4988 stepper motor driver board. Luckily there was enough space within the headers to fit the 3.3 V to 5 V inverter circuit. The four phases and the associated connector can be seen in the middle of the left header for the A4988. The bottom-most pin of this left header interface with the 12 V power plane.

The layout for the food station proved to be more difficult due to the lower number of parts compared to the water station. There were several design constrains imposed by choosing the A4988 carrier board instead of implementing the carrier board ourselves. If given additional time, it would be preferable to integrate the two onto a singular PCB. Yet again, the supply chain issues limited the supply of A4988 to solely those on carrier boards. Hence, the team would have to purchase the carrier board, remove the A4988, and effectively copy the existing circuit in the documentation. Hopefully, those reading this document will agree that time and resources were better spent elsewhere.

As seen in the figure, the left header pin required the 5 and 12 V rails be applied at both ends. Since only the A4988 requires the 12 V supply it presents freedom in where the 12 V plane may be located. Under the current design, the length of the board in the horizontal direction is minimized. Improvements could be made to make the board smaller such as rotating the A4988 clockwise by 90 degrees. However, there would be an incredibly large amount of dead space below the chip. Therefore, the size of the 5 V plane was increased to try and minimize this horizontal distance instead of vertical distance.

A second revision was necessary due to a minor oversight in the headers. Within Kicad there exists the option to move one component with respect to another by some exact distance. This feature was used to ensure the distance between the header pins of the ESP were exactly 0.9 inches apart. However, when the header pins were imported into the schematic it was not verified that the top-most pin corresponded to the respective pin in the schematic. Sadly, one header pin was rotated 180 degrees with respect to the other and all the GPIOs, various signals, and power were applied to the incorrect pins. In this second version, the connections were corrected and some optimizations in the number of total GPIOs were implemented. One such example is in the MS pins of the A4988. There are three digital pins MS1, MS2, and MS3 which select the stepping mode of the driver. There was no intention of running the motor outside of a full step, hence, the three pins are tied to ground forcing the motor to always operate in full step.

After receiving the PCB, no further issues were found. The 3D render for the PCB is provided in the figure below. Note, the food station PCB was created entirely under a Kicad 6.0 project, implying the bug mentioned in the water station did not remove the 3D model for various passives. The final dimensions of the board are 2.6 by 2.0 inches.

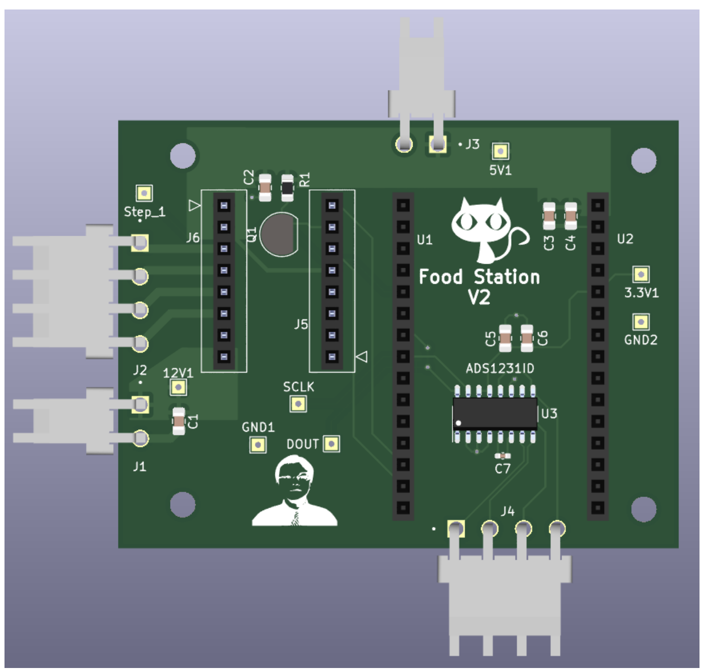

Figure 52: Finalized food station PCB 3D render.

12.2.3 Power Board

The power board, albeit the most time intensive board to design was relatively the simplest. The completed layout is provided in the figure below.

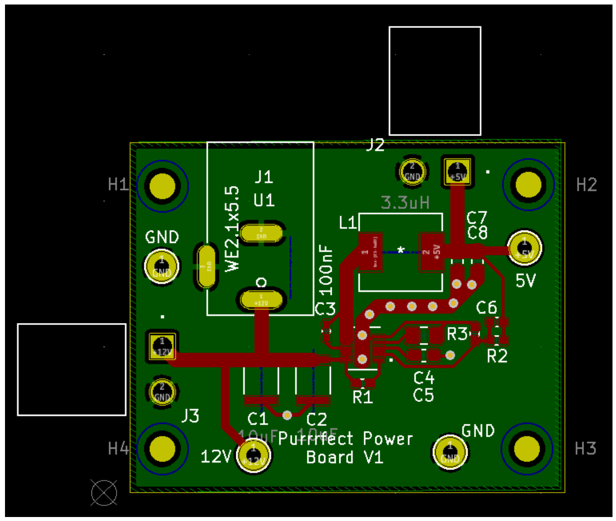

Figure 53: Finalized power board PCB layout.

The TPS54328 provides layout guidelines in the data sheet. The general concern throughout the design was the switch node, proper grounding, and trace width. The TPS chip allows for a maximum output current up to 3 A. If any station were to draw 3 A from the supply, it is incredibly likely that something bad has occurred. Typically a 3 A trace would require on the order of 50 mil traces. A compromise was made by choosing 40 mil traces. The 40 mil traces on the input, output, switch, and ground nodes allows for a maximum current near 2 A.

The TPS chip is present in the center of the board. All nearby passives have been sized according to the reference design by WeBench. Many of the resistors are 0402 sized, but the capacitors vary from the large 1210 input capacitors to the 0404 bootstrap capacitor. The large block above the TPS is the 3.3 μH inductor. To the left of the inductor is the switch node. It was recommended in the guidelines to route the switch node away from other sensitive components. Although there are no sensitive components nearby the inductor, the trace was far enough such that the inductor could fit comfortably away from the passive elements. The large trace with several vias embedded represents the power ground. The guidelines state that the vias aid in creating low impedance paths to ground along the trace. The last components, C4 through C6 and both R2 and R3 form the feedback network and internal biasing components. The TPS chip requires some sort of feedback mechanism to control wether to increase or decrease the output voltage. The additional capacitor, C6, is present to siphon noise from the feedback pack. Additional capacitors are present to properly bias the TPS chip.

The finalized power supply board is provided in the figure below. The final dimension of the board is 1.5 x 1.2 inches.

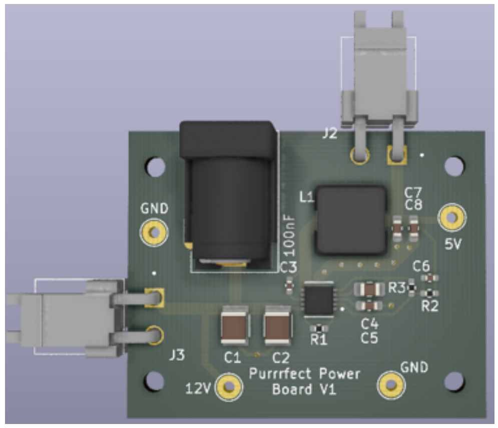

Figure 54: Finalized power board PCB 3D render.

12.3 Device Housings

In today's industrial climate, the economic effectiveness and environmental friendliness of a production process are critical. Therefore, the team opted to custom 3-D print the body of the water and feeder system. 3-D printing offers unique advantages form a design, time and cost prospected.

The process of 3-D printing starts with a single axis (X axis) and progresses to the Y-axis. After completing the first two axes, it advances to the Z-axis, which adds thickness to the object and results in a solid 3D model. The design from the computer is sent into the 3D printer through a software interface.[34] 3-DP technology can convert complicated geometry into a physical representation than with traditional manufacturing procedures. Traditional techniques have design constraints that are no longer applicable with the usage of 3-D printing. Since, 3-D printing can produce parts in hours, expediting the prototype process. This allows each step to be completed more quickly and the ability to modified individual parts during the prototype stage. As they are printed using a 3-D model as a CAD or STL file, the 3-D design files are all saved in a virtual library and can be found and printed as needed. Individual files may be edited to make design changes at any given time.[106]

While certain metal can also be utilized, PLA (Polylactic Acid) is one of the most used material in 3-D printing. The lighter weight compared to metal would result in substantial light water and feeder stations lighter compare to some available on the market. Polylactic acid is produced mostly from renewable or green sources such as sugar cane, starch, and maize. For example, corn kernels are delivered and milled; dextrose is extracted from starch. Huge fermenters convert the dextrose into lactic acid, and lactide molecules are linked into long chains or polymers: polylactic acid, PLA.[108] As a result, it is easily recyclable. It is utilized in most additive manufacturing procedures that use plastic-based materials to create 3-D models and prototypes.[144]In comparison to alternative technologies that cut from big pieces of non-recyclable materials, the creation of components requires just the resources needed for the part itself, with little or no waste. The procedure not only saves resources, but it also lowers the cost of the materials utilized. [106]

Even though PLA offers many advantages, when it comes to design flexibility food grade approval is nonnegotiable. Plastic is frequently seen as an inert, sterile material. However, under the correct conditions, it will deteriorate. These properties differ from one plastic to the next, with certain plastics taking very long to degrade. So much that they are frequently compared to nuclear waste with a large half-life. Some questions one may ask are: Does common 3D printing material PLA deteriorate? Should PLA be in contact with food? and Can PLA leak microplastics into water? In 1995 an experiment titled the Safety assessment of polylactide (PLA) for use as a food -contact polymer was published.

They tested PLA in a range of common food storage circumstances and examined what leached out into food-simulating solvents including ethanol and acetic acid. With a variety of short- and long-term storage circumstances, the storage conditions were varied. Some samples were even heated to 60°C to imitate food service settings. Their summary concluded that PLA releases small quantities of lactic acid into meals. Lactic acid is a frequent food additive, and it can even be present in breast milk. They calculated that the quantity of lactic acid humans would ingest from PLA would be approximately 700 times less than the amount of lactic acid consumed by breast-fed newborns. Therefore, PLA was determined to be Generally Recognize As Safe (GRAS) when utilizes in contact with food in the study.[34] The following are some of the standards use to determine a conclusion.

- The tensile plate was fabricated with the ASTM standard 638 type 5 (Standard Test Method for Tensile Properties of Plastics).
- The tensile plate was fabricated with the ASTM standard D790 (Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials).
- Impact test specimen was fabricated with the ASTM standard D256 (Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics)

Even though PLA is food safe, there are a few things to consider

- The majority of PLA is colored. As a result, different additives have been added to the PLA to give it a unique color. Therefore, printing anything that will come into touch with food would be advantages to use 'virgin' or 'natural' PLA which is not the case for the PLA used to print the water and feeder stations.[128]
- Several 3D printers' hot ends include elements that are unsafe for human consumption. So, if an all-stainless steel is not utilized in the processes, trace amount of toxins may make their way from the printer's hot end to the model, and then into the contact food.[128]

- Keeping your printed products clean will be nearly impossible. 3D printouts are riddled with holes and crevices. When these tiny holes become clogged with food, they become a breeding ground for bacteria that can cause a serious case of food poisoning. Prints that come into touch with food should be considered disposable and discarded after usage.[128]

Now, it needs to be determined what does food safe really mean. There are three important key terms to clarify.

- The term ”food grade” denotes that the substance is either safe for human eating or can come into touch with food.
- Food safe indicates that a food grade substance satisfies the standards of its intended application and will not cause a food safety hazard.
- Food contact surfaces include any surface that may come into direct contact with food. These surfaces must be manufactured of harmless materials and built to endure the environment in which they will be used, including cleaning substances, sanitizing agents, and cleaning techniques.

Food grading and food safety are concerned with a specific method of ingesting pieces known as migration. Particles as tiny as a few nanometers and as large as several hundred nanometers may be transmitted when different materials come into contact with one other, such as when components of the 3D printer come into contact with the 3D printed object, and the object comes into contact with the meal. Because migration levels are relatively low with infrequent contact, food grading primarily concerns things that come into touch with food on a regular basis, including containers, straws, utensils, plates, and food molds. Different testing institutions will conform to different government-imposed risk tolerances and permitted compounds, which are detailed in the FDA CFR 21 for the United States and EU guidelines. Also, materials being ‘compliant with’ does not imply that it has been officially authorized by the institutions. The product must specify FDA and EU approval, this may be verified by consulting the technical datasheets where the certifications are located. In order to be considered food safe according to the FDA food code, a material must meet the following requirements:

- No migration of deleterious substances.
- Does not impart colors, odors, or tastes.
- Safe under normal use conditions.
- Durable, corrosion-resistant, and nonabsorbent.
- Sufficient in weight to withstand repeated washing.
- Finished to have a smooth, easily cleanable surface without breaks and sharp internal angles.

- Resistant to pitting, chipping, crazing, scratching, scoring, distortion, and decomposition
- Accessible to inspection.

Any FDA or EU-approved item contains not only the raw polymer but also any additives or masterbatch which might contain plasticizers, impact and heat distortion modifiers, UV-stabilizers, flame retardants, anti-fouling, anti-static, anti-slip, foaming and clarifying agents, antioxidants, aromatic nucleators, carbon alloys, phosphorescent, fillers, thickeners, chain extenders, metal deactivators, dyes, and a carrier resin may be present.[66]

Filament	Brand	FDA	EU	Smoothable	Dishwasher Safe	Hot Liquids
PLA	Filaments.ca TrueFS	Approved	N/A	X	X	X
	Filamentum	N/A	Compliant	X	X	X
	Innofil3D	Approved except red, orange, pink, apricot skin, grey, and magenta)	Approved except red, orange, pink, apricot skin, grey, and magenta)	X	X	X
	Copper3D PLActive Antibacterial	Approved	Compliant	X	X	X
	Makergeeks	Approved	N/A	X	X	X
	Purement Antibacterial	Approved	Approved	X	X	X
PLA-HT	Makergeeks Raptor	Approved	N/A	X	Yes	Yes

Table 19: PLA approval and properties comparison.

Running pieces through the dishwasher eliminates PLA since these polymers soften and distort at 60–70 °C, yet most soap manufacturers design their soap to perform best in water temperatures ranging from 49 to 52 °C. [24] As previously stated, the Food and Drug Administration's Center for Veterinary Medicine recommends that pet owners wash their pet's food and water bowls with hot, soapy water after each meal and water bowls every couple of days, according to William (Bill) Burkholder, DVM, PhD, DACVN, and Charlotte Conway, MS. Even though PLA is not dishwasher safe, it can still be used for the project since the suggested temperature for cleaning the bowl is soapy hot water (49 to 52 °C), which is lower than the temperature at which PLA becomes warped (60–70 °C).

Having a better understanding of the characteristics of 3DP and PLA with respect to food safety, the team is forced to look for alternative material. It is the team's duty to design a solution which does not harm the cat or any users interacting with the system. Since the printed bowl would only contain room temperature water and dry cat food, there is no need to be concerned about the model being exposed to raw meat or eggs, which are more prone to dangerous bacteria formation. A great alternative would be coating the printed product by using food safe epoxy or sealer to block up the crevices where germs can accumulate in.

It is necessary to understand the characteristics and benefits of utilizing different types of sealers in order to pick the appropriate one. After a thorough investigation on the internet, epoxy resin was classified as one of the must popular materials in a variety of industries since it has greater heat and chemical resistance, as well as stronger mechanical qualities than other forms of resin. When epoxy resin is liquid, it is poured into a mold or painted over a substance in layers to form a protective outer covering. The substance hardens into a solid after curing, becoming durable and structural study. Because of this mix of properties, epoxy resin is particularly helpful in a wide range of applications, from automotive manufacturing to arts.

The polymerization processes and chemical compound will impact the resulting core characteristics of an epoxy resin formula. Some of the trademark properties of epoxy resin include chemical stability, anti-corrosive, food safe, absence of VOCs (volatile organic compounds) to mention a few. In order to obtain optimal strength and performance, the epoxy resin producers should offer instructions on the epoxy to hardener ratio that should be employed. To start this procedure, the epoxy resin is combined with the co-reactant (hardener), which is normally package in a separate compartment. The chemical reaction starts as soon as the chemicals become in contact with each other, and depending on the formulation can solidify rapidly or slowly; depending on the application it which it was designed.[129]

Casting and coating epoxy resins are two unique yet related compounds. Ultimately, the choice between the two will determined how the finish product will appear and perform. Casting resins are used for clear encasing and suspensions. The material is poured into a mold and then cure to keeps its form. Casting resins are widely utilized in the production of crafts, jewelry, sculpture, and souvenirs. Also, engineers use epoxy resin to manufacture automobile components, aircraft gadgets, sports equipment, and hundreds of other goods. On the other hand, coating resins as the name implies, is used to coat material as metal, concrete, or wood in order to make them stronger, chip-resistant, simpler to clean, water-resistant, and rust-proof. Interesting fact, coating resins are applied to circuits and transistors in the electrical manufacturing industry to hold components together and protect against corrosion. [129]

Aside from these application differences, there are a few more noticeable differences between casting and coating epoxy resin. Casting resins are often thinner than coating resins in terms of viscosity. Since liquid casting resin is poured in thick layers, it takes longer to cure to prevent shrinkage and heat buildup. Coating resins are often stiffer and more difficult to work with than casting resins. Most coating resins employ a 1:1 ratio, although casting resin formulations might vary. The viscosity of a liquid defines its resistance to flow. The viscosity of epoxy resin formula impacts whether the substance will drip or spread uniformly and whether it should be poured, dipped, or painted on the material. The amount of epoxy that perforates the substrate and the physical qualities that are formed are also affected by the viscosity.[129]

After an intense investigation on epoxy resins, ArtResin™ has the quality and safety that is require for the food and water base stations. ArtResin™ has been certified by the American Society for Testing and Materials as non-toxic when used as directed (conforms to ASTM D4236). Formulated using the highest quality materials and no solvents or fillers, ArtResin™ is a clean system and contains no non-reactive diluents, meaning that all components of the resin react completely with all the components of the hardener, leaving no VOCs, fumes or anything else that could become airborne and cause health issues. For all these reasons, ArtResin™ is classified as a non-hazardous material, is safe for use at home, requires no respirator and is safe for direct contact with food. Once ArtResin™ is cured, it becomes food safe as per FDA 21CFR175.300 (safe for direct food contact). Furthermore, Epoxy resins in general are prone to yellowing and other degradative effects from UV light, so UV stabilization additives are used in manufacturing to help protect against gloss loss, cracking, chalking and de-lamination, and to some extent yellowing. A UV stabilizer on its own does not prevent but merely delays yellowing in resins. For this reason, ArtResin™ also includes a HALS (hindered amine light stabilizer) which interrupts the yellowing process, ensuring extremely effective long term non-yellowing protection. [127]

Some tips to fallow in order to make sure the application of the resin comes out as desire. The PLA should be clean and dry. The working environment should be free of dust. Due to the limited number of hours available to work before the resin solidifies, all essential instruments should be acquired prior to beginning the application. Also, ArtResin™ should be at room temperature (72-77°F or 23-25°C) and should not fluctuate for the first 24 hours while curing. The following are the instructions on how to use ArtResin™[127]:

- Prop your piece up on stands and make sure it's level.
- Measure the desire amount needed. With gloves on, pour precisely equal amounts of room temperature resin and hardener into a mixing container.
- Stir thoroughly for at least 3 full minutes, scraping the sides and bottoms as you stir to ensure that the entire mixture will properly catalyze and therefore cure as expected. There is about 45 minutes of working time.
- Pour and spread as necessary. ArtResin™ is a self-leveling. It's recommended to use foam brush for 3D surfaces.
- Bubbles will start to appear on the surface. To get a faultless finish, it is advised that you use a torch to pop bubbles. It is ideal to work in a clean and well-lit environment for best outcomes.

- Once the resin has been applied, it may be covered to protect it from dust and left overnight to cure. The sculpture will be hard to the touch in around 24 hours and fully cured in 72 hours.

There are two possibilities for pouring numerous layers.

1) Pour the first layer, torch out the bubbles, cover, and leave to set for 3-5 hours, or until it achieves a jelly-like consistency. Pour on the next 18" layer, torch out bubbles, cover, wait 3-5 hours, and continue until you reach the desired height. This procedure is very useful when pouring into a mold.

2) Allow the first coating to dry completely, then sand the sculpture lightly all over before pouring on your next 1/8" layer. Remove any bubbles, cover, and allow the coating to dry. These instructions can be repeat it as many times as desire. As mentioned earlier, the 72-hour cure period is based on an 1/8" layer. The longer the cure period, the thicker your layers.

12.4 Finalized Stations

The following sections will provide figues showing the completed housing, including electronics for each of the stations. The intent of this section is to supplement the visualizations provided in the final demonstration video.

12.4.1 Water Station

Figure 55: Completed water station.

As shown in the figure above, the water station housing is divided into two compartments. The back compartment acts as the water reservoir. As mentioned, a liquid level sensor is present to detect the level in the reservoir. To insert the sensor into the housing required a small hole be drill into the reservoir section. This hold could introduce flooding into the other compartment if the level sensor's seal were damaged. In the case of flooding, 3D printed standoffs were printed. The standoffs are several inches high and elevate both the electronics and the pump off the floor of the non-reservoir compartment.

In the figure a brief view of the internal electronics is shown. The pump was attached to the divider between the reservoir and electronics compartments. The general electronics are raised from the bottom of the housing due to the standoffs, and one of the connectors is seen routing the load cell wires between the load cell and the PCB. To account for the DC wall plug, a small hole was drilled to allow the connector to maintain a tight fit with the station. Stemming from the station is a 3D printed bowl holder which holds a stainless steel pet bowl. The tubing from the pump is inserted through a 3D printed model of our mascot (The image on the title slide) to securely hold the tubing. Overall, the station is large enough to hold a sufficient quantity of water but also compact enough to be placed conveniently through the house.

12.4.2 Food Station

Figure 56: Completed food station.

Due to the construction of the food station, it is difficult to show both the completed housing and the internal electronics. Beginning with the transparent tube, this tube was purchased from home depot and interfaces with a 3D printed hopper. The hopper roughly aids in slowing down the flow rate of food into the auger and relieving the weight of the food reservoir from overloading the auger. The horizontal cylinder includes the auder and a housing around it. The housing is necessary or else food will fall off the auger. The implemented augor is provided in the 3D printing sections of the report. Just below the auder is the same food bowl holder and stainless steel bowl as the food station. The same mechanism was reused since having the freedom to shift the bowl by a few centimeters was helpful when testing various dispense amounts. The final component, the slim box holds all the internal electronics, and nothing notable is present within it.

12.4.3 Waste Station

Figure 57: Completed waste station.

The waste station, in favor of simplicity, build circuits on perfboard-like prototype boards. The various circuits were hand soldered onto small chunks of PCBs and hot glued to the housing of the litter box. It is acknowledged that asking owners to hot glue data modules to their devices is unrealistic. In a proper implementation, the individual circuits boards would be housed within a small box. Each of these small boxes could have double-sided tape attaching it to the box. Tangent aside, leaving the exposed circuitry provides better insight into how the circuit is constructed.

On the right-side of the figure is the receiver segment of the IR transciever. On the opposing side of the litter box is the transmitter and wires are routed within the curves top, or lip of the box. Continuing along the rim of the box is a black square which represents the humidity sensor. The sensor was placed at the back end of the box to provide the greatest probability of detecting if the cat urinated or not. Regardless if a cat turns around within the box, the net motion of moisture is likely towards the humidity sensor. Just below the humidity sensor is the ESP, 555 timer, various connectors to the IR transciever and the humidity sensor, and last of all the power supply board.

13 Administrative Content

Any real engineering project cannot exist solely in the realm of design and mathematics. Real-world considerations must be made for budgeting, scheduling, distribution of responsibilities, and choosing manufacturers and providers for the parts. This chapter outlines the administrative concerns of the project and information useful to those attempting to recreate the project. The chapter will also include various plans for prototyping, testing, and construction of the final product.

13.1 Budget

A large focus of this project is cost. According to the market research done at the start of the project, it was determined that each automatic system can cost in the ranges of $30-$300. It is not the goal of this project to make a better, or more competitively priced product. Instead, the goal is more in elevating the current technology to provide data to a pet owner, veterinarian, or animal shelter owner, while keeping costs low for the team. Therefore, there any new development will incur some costs in the form of physical parts, testing software, or formal documentation if needed, but will be minimized as much as possible. At the end of Senior Design 1, the initial budget set by the team was $500.

As mentioned, it is not the intent to develop a competitive product. In the pursuit of elevating a system that surpasses current technology, this resulted in an over-budget product that which met the aforementioned goals in Chapter 2.3. In the following sections, the Bill of Materials explain what expenditures were made for each subsystem. They cover the total cost of one board for Figures 59, 60, and 61. For Figure 62, the total cost to develop three power boards are shown. It is important to note, the BOMs for each section does not indicate total expenditures for the entire project.

In Figure 58, a general overview of total expenditures include a collection of components that met the requirements for the project. Such expenditures include on the spot orders of motor drivers, ADCs, or even board redesign. The core components block indicates purchases of the same components shown in the BOMs for each subsections, however these are iterative purchases in order to account for mistakes in PCB integration and system modification. Miscellaneous components relate to tools, supplies, and mechanical hardware. Finally the cost of manufacturing the PCB shows three respins of the design. Each order included multiple instances of the same board and in some cases for one subsystem. In order to keep this overhead cost at a low, the revisions of each board required further testing to ensure all bugs in the PCB designs were fully covered. Repeated orders to the vendor would result in weeks of down time if this were not observed. All these considerations indicate that the over-budget cost relating to the R&D, testing, and system integration pushes the total cost of $647 well over the initial estimate of $500.

	Item	Manufacturer	Price/Unit	Qty.	Total Cost
Core Components	Mini Water Pump, Submersible Micro Brushless, Food Grade	Amazon	$15.49	1	$15.49
	ADS1231ID	Texas Instruments	$7.33	2	$14.66
	Digital Load Cell Weight Sensor HX711 AD Converter Breakout	MakerHawk	$12.99	1	$12.99
	ANALOG LIQUID LEVEL SEN	DFRobot	$8.90	1	$8.90
	IC REG BUCK ADJUSTABLE 3A 10VSON	Texas Instruments	$1.79	5	$8.95
	WL-OCPT OPTOCOUPLER PHOTOTRANSIS	Würth Elektronik	$0.36	2	$0.72
	OPTOCOUPLER DARLINGTON 6DIP	Isocom Components	$0.66	2	$1.32
	Steper Motor/ WO-417-11-18-ND	Lin Engineering	$41.26	1	$41.26
	Load Cell - 5kg, Straight Bar (TAL220B)	SparkFun	$10.95	3	$32.85
	Digital Temperature and Humidity Sensor	Adafruit Industry LLC	$3.95	2	$7.90
	AM2320 Digital Temperature And H	Pimoroni Ltd	$3.90	2	$7.80
	ESP82666	NODEMCU	$7.99	1	$7.99
	*Water Coffee Flow Hall Sensor Switch Meter	Digiten	$9.49	1	$9.49
	SENSOR REMOTE REC 38.0KHZ 2M	Vishay Semicindonctoe Opto Division	$1.12	2	$2.24
	EMITTER IR 940NM 100MA RADIAL	Vishay Semicindonctoe Opto Division	$0.52	2	$1.04
	IC OSC SINGLE TIMER 100KHZ 8-DIP	Texas Instruments	$0.50	2	$1.00
	IC ADC 24BIT SIGMA-DE;TA16SOIC	Texas Instruments	$7.33	2	$14.66
	Digital Load Cell Weight Sensor (Backup for TAL220B)	MakerHawk	$12.99	2	$25.98
	A4988 Driver Board	Pololu	$10.99	3	$32.97
	DC Wall Plug	Qualtek	$9.81	3	$29.43
Passives	Resistors, Capacitors, Transistors, and Testing Components	DigiKey	N/A	N/A	$195.23
Miscellaneous	100ml Graduated Cylinder	Lake Cherles Manufacture	$8.99	1	$8.99
	A886R-ND	Aries Electrics	$5.20	2	$10.40
	SRA Soldering Products Rosin Paste Flux #135 In A 2 oz Jar	SRA	$8.99	1	$8.99
	63-37 Tin Lead Rosin Core Solder Wire for Electrical Soldering	MAIYUM	$10.89	1	$10.89
	SW02-10 No-Clean Solder Wick, 4 Blue.098" Width, 10' Length	NTE Electronics	$11.12	1	$11.12
	SMD to DIP Breakout for SOIC-16, TSSOP-16, MSOP-16, and VSOP-16	Stargazer Labs	$8.99	1	$8.99
	SMDLTLFP Solder Paste	Chip Quik	$15.95	1	$15.95
	Socket Adapter Soic to 16Dip	Aries Electrics	$5.20	2	$10.40
	Socket Adapter Soic to 16Dip	Amazon (Stargazer)	$8.99	1	$8.99
	Prototype PCB Variety Pack	Amazon (DEYUE)	$11.99	1	$11.99
Manufacturing	PCB Order 1	JLCPCB	$17.80	1	$17.80
	PCB Order 2	JLCPCB	$26.13	1	$26.13
	PCB Order 3	JLCPCB	$22.86	1	$22.86
Total					**$646.37**

Figure 58: Total Expenditures.

13.2 Bill of Materials

The budget section 13.1 does not accurately capture what components are necessary to recreate the project. The following tables will breakdown, by station, what must be purchased to recreate each station.

13.2.1 Water Station

The water station bill of materials is provided in the chart below.

(Intentionally left blank)

Item	Qty	Reference(s)	Part Type & Value	Footprint & Part No.	Manufacturer	Cost (/ea)
1	4	C1, C4, C7, C8	10uF	0805/C0805C106K3PAC7800	Kemet	$0.27
2	3	C2, C3, C9	1uF	805/C0805C105K3RAC7800	Kemet	$0.13
3	1	C6	1nF	805/C0805C102K5RAC7800	Kemet	$0.12
4	1	C10	0.1uF	402/C0402C104K8RACAUTO	Kemet	$0.11
5	1	D1	1N4007	S1D-13-F	Diode Inc.	$0.30
6	2	J1, J4	4-pin Male Header	TE_1744428-4	TE Connectivity	$0.47
7	3	J2, J3, J5	2-pin MaleConnector	TE_1744428-2	TE Connectivity	$0.39
8	2	J1, J4	4-Pin Female Housing	TE_1744416-4	TE Connectivity	$0.46
9	3	J2, J3, J5	2-pin Female Housing	TE_1744416-2	TE Connectivity	$0.24
10	14	J1, J2, J3, J4, J5	Connector Crimps	TE_1744144-1	TE Connectivity	$0.13
11	1	Q1	N-channel MOSFET	TO-220F/STF10N65K3	STMicroelectronics	$1.75
12	2	R1, R2	100kΩ	805/RC0805JR-07100KL	YAGEO	$0.04
13	1	R3	500Ω	805	HiLetgo (SMD pack)	$0.02
14	1	R4	360Ω	805	HiLetgo (SMD pack)	$0.02
15	1	R5	4.7kΩ	805/RC0805JR-104K7L	YAGEO	$0.04
16	1	R6	220kΩ	805	HiLetgo (SMD pack)	$0.02
17	1	R7	160Ω	1210/ERJ-P14J161U	Panasonic	$0.03
18	2	U1, U2	15-pin Female Header Pins	PPTC151LFBN-RC	Sullins Connector Solutions	$0.98
19	1	U3	Optocoupler	4N32	Isocom Components	$0.66
20	1	U4	Load Cell Amplifier	ADS1231ID	Texas Instruments	$7.33
21	1	N/A	ESP8266	N/A	NodeMCU	$8.99
22	1	N/A	DC Wall Plug	QFWB-20-12-US01	Qualtek	$9.81
23	1	N/A	Pump	N/A	Gikfun	$12.78
24	1	N/A	Level Sensor	SEN0205	DFRobot	$8.90
25	1	N/A	Load Cell	TAL220B	Sparkfun	$11.59
					Total:	**$65.58**

Figure 59: Water station bill of materials.

13.2.2 Food Station

The food station bill of materials is provided in the chart below.

Item	Qty	Reference(s)	Part Type & Value	Footprint & Part No.	Manufacturer	Cost (/ea)
1	4	C1, C2, C4, C5	10uF	0805/C0805C106K3PAC7800	Kemet	$0.27
2	1	C3, C6	1uF	0805/C0805C105K3RAC7800	Kemet	$0.13
3	1	C7	0.1uF	0402/C0402C104K8RACAUTO	Kemet	$0.11
4	2	J1, J3	2-pin Male Header	TE_1744428-2	TE Connectivity	$0.39
5	2	J2, J4	4-pin Male Header	TE_1744428-4	TE Connectivity	$0.47
6	2	J1, J3	2-Pin Female Housing	TE_1744416-2	TE Connectivity	$0.24
7	2	J2, J4	4-pin Female Housing	TE_1744416-4	TE Connectivity	$0.46
8	14	J1, J2, J3, J4, J5	Connector Crimps	TE_1744144-1	TE Connectivity	$0.13
9	2	J5, J6	8-pin Female Header	PPTC081LFBN-RC	Sullins Connector Solutions	$0.65
10	1	Q1	N-Channel MOSFET	ZVN4310A	Diodes Inc.	$1.74
11	1	R1	1k	805	HitLetgo (SMD pack)	$0.02
12	2	U1, U2	15-pin Female Header Pins	PPTC151LFBN-RC	Sullins Connector Solutions	$0.98
13	1	N/A	Load Cell	TAL220B	Sparkfun	$11.59
14	1	U3	Load Cell Amplifier	ADS1231ID	Texas Instruments	$7.33
15	1	N/A	Stepper Motor	42BYGHW811	Wantai Motors	$17.95
16	1	N/A	ESP8266	N/A	NodeMCU	$8.99
17	1	N/A	DC Wall Plug	QFWB-20-12-US01	Qualtek	$9.81
					Total:	**$61.26**

Figure 60: Food station bill of materials.

13.2.3 Waste Station

The waste station bill of materials is provided in the chart below.

Item	Qty	Reference(s)	Part Type & Value	Footprint & Part No.	Manufacturer	Cost (/ea)
1	1	C1	1uF	N/A (Present in lab)	N/A	$0.05
2	1	C2	10uF	N/A (Present in lab)	N/A	$0.05
3	2	C3, C4	0.01uF	N/A (Present in lab)	N/A	$0.05
4	1	D1	IR Transmitter	TSAL4400	Vishay Semiconductors	$0.52
5	1	D2	Discharge Diode	IN4007	N/A (Present in lab)	$0.05
6	2	J1	15-pin Female Header Pines	PPTC151LFBN-RC	Sullins Connector Solutions	$0.98
7	1	J2	4-pin Male Header	TE_1744428-4	TE Connectivity	$0.47
8	1	J3	2-pin MaleConnector	TE_1744428-2	TE Connectivity	$0.39
9	2	R1, R2	10kΩ	N/A (Present in lab)	N/A	$0.05
10	1	R3	370Ω	N/A (Present in lab)	N/A	$0.05
11	1	R4	1.3kΩ	N/A (Present in lab)	N/A	$0.05
12	1	R5	1.8kΩ	N/A (Present in lab)	N/A	$0.05
13	1	U1	Signal Generator	LMC555CN	Texas Instruments	$1.69
14	1	U2	IR Receiver	TSSP4038	Vishay Semiconductors	$1.12
15	1	N/A	ESP8266	N/A	NodeMCU	$8.99
16	1	N/A	DC Wall Plug	QFWB-20-12-US01	Qualtek	$9.81
17	1	N/A	Traditional Litter Box	N/A	Target	$4.99
					Total:	**$29.36**

Figure 61: Waste station bill of materials.

13.2.4 Power Board

The power board bill of materials is provided in the chart below.

Item	Qty	Reference(s)	Part Type & Value	Footprint & Part No.	Manufacturer	Cost (/ea)
1	2	C1, C2	10uF	1210/GRM32ER71J106MA12L	Murata Electronics	$0.97
2	1	C3	100 nF	0402/C0402C104K8RACAUTO	Kemet	$0.11
3	1	C4	3.3nF	0805/GRM219R72A332KA01D	Murata Electronics	$0.21
4	1	C5	1uF	0603/C0603C105Z4VAC7867	Kemet	$0.11
5	1	C6	5.1p	0402/GRM1555C1E5R1CA01D	Murata Electronics	$0.03
6	2	C7, C8	22uF	0603/C1608X5R1A226M080A(	Murata Electronics	$0.34
7	1	J1	DC Jack	6.94106E+11	Würth Elektronik	$0.99
8	2	J2, J3	2-pin MaleConnector	TE_1744428-2	TE Connectivity	$0.39
9	1	L1	3.3uH	MPEV1D0630L100	Kemet	$1.46
10	1	R1	10k	0402/CRG0402F10K	TE Connectivity	$0.10
11	1	R2	133k	0402/CR0402-FX-1333GLF	Bournes Inc.	$0.10
12	1	R3	24k	0402/ERJ-U02F2402X	Panasonic Electronic Components	$0.12
13	1	U1	TPS54328DRCT	TPS54328DRCT	Texas Instruments	$1.79
					Invididual Total:	**$6.73**
					Total Cost (3x):	**$20.18**

Figure 62: Power board bill of materials.

13.3 Milestones

The successful completion of the project required a number of different positive practices discussed in the Senior Design bootcamp. The main observations of these practices include iden-

Milestone	Task	Start	End	Status	Responsible
1	Brainstorming	6/22/2021	7/12/2021	Complete	Group 18
2	Project selection	7/21/2021	7/28/2021	Complete	Group 18
3	Block diagram development	8/23/2021	8/30/2021	Complete	Group 18
4	Role assignment	9/6/2021	9/6/2021	Complete	Group 18
5	Initial divide and conquer	9/10/2021	9/17/2021	Complete	Group 18
6	Senior Design I Document	9/17/2021	11/24/2021	Complete	Group 18
7	Component research	8/23/2021	9/17/2021	Complete	Group 18
8	Schematic development	10/1/2021	10/22/2021	Complete	Michael
9	PCB design	10/1/2021	10/22/2021	Complete	David
10	Base station development	10/1/2021	11/1/2021	Complete	Will
11	Firmware development	10/1/2021	11/1/2021	Complete	Carla
12	Power supply development	10/1/2021	11/1/2021	Complete	Hector
13	Food station development	11/1/2021	12/1/2021	Complete	David
14	Water station development	11/1/2021	12/1/2021	Complete	Hector
15	Waste station development	11/1/2021	12/1/2021	Complete	Michael
16	System integration and testing	11/14/2021	12/3/2022	Complete	Group 18
17	Prototype testing	1/10/2022	2/28/2022	Complete	Group 18
18	Finalize product	3/1/2022	3/31/2022	Complete	Group 18
19	Peer presentation	3/15/2022	4/1/2022	Complete	Group 18
20	Final report	4/1/2022	4/8/2022	Complete	Group 18
21	Final presentation	4/8/2022	4/22/2022	Complete	Group 18

Table 20: Senior Design milestone schedule.

tifying team values, experiences in previous project lessons, project risks, and each team members' strengths, weaknesses, and constraints as well as what success looks like. The team integrated time management sessions in which to ensure progress was being made at key milestones mentioned in Table 20. Although this was a challenging practice to observe, the team made the best of every situation and maintained flexible meeting practices in order to accommodate each team member's particular situation. The use of the milestone table enabled a clear view of what challenges were completed and what to account for down the road. In order to efficiently eliminate each challenge, the team provided a number of tasks each team member was responsible for, along with a defined window of execution.

Throughout the project, various milestones were hit on schedule and others not. The following sections will discuss the various plans and breakdown of work, however, assigning each member to work on unrelated parts of each substation introduced bottlenecks. For example, the prototype testing for the water station was completed by February 28th but the food station prototype was completed late March. Issues such as PCB revisions, parts shortages, and firmware development occurs relatively asynchronously leading to difficulties keeping to a hard schedule. Many lessons were learned which the team will take forward into their careers.

13.4 Planning Stages

The following sections will discuss at a high-level the breakdown of work necessary to design, construct, and test the final implementation. The teams meetings were split across zoom, the eli^2 office in Engineering 1, and the Senior Design lab in Engineering 1. Throughout prototyping, the equipment in the Senior Design lab was used exclusively. Within the lab, common resistor and capacitor values were available. Common test equipment such as oscilloscopes, function generators, variable DC power supplies, and digital multimeters were used extensively throughout development.

13.4.1 Design

The term design phase is used to encompass Senior Design 1. Throughout the design phase, each station was broken into hardware and software components. Each of these components was assigned a lead who was responsible for progress and resolving design issues. To ensure no station was left stranded if an unfortunate event were to happen to any team member a secondary was assigned. Together, each primary and secondary would independently work on their station or assist with another station.

The progress of each hardware and software component was up to the discretion of the primary. Documentation of the current progress, future goals, and current tasks were documented in discord and verbally to those assisting with the station. To compile semesters worth of conversations and messages into a single design plan is beyond the scope of this document. It is the team's hope that explaining our process of developing each station at a high-level is sufficient.

13.4.2 Construction

Moving onto the construction of each station, more time was invested in assigning deadlines and writing a formal plan of tasks to be done. The general plan included allocating a month for each station. During this month the station would be prototyped, constructed, and integrated with the other stations. In order, January was dedicated to the water station, February to the food station, and March to the waste station. The entirety of April was dedicated to integration of all three stations, resolving bugs, and any last-minute issues. The allocation of each month was to prioritize progress on each station, however, it did not imply that progress on the other stations would stagnate. Throughout the water station's development, the primary and secondary structure was not sufficient in resolving some design issues. Hence, the additional time relieved the burden of potentially requiring each station be done within a month or two.

The construction of each station actually began throughout Senior Design 1. Each of the circuits in the final implementation were prototyped on breadboards during Senior Design 1. The prototype phase in Senior Design 2 was focused on improvements to the prototypes developed in Senior Design 1. Some improvements included changes to components, preliminary layout on the breadboard, and firmware development. lThe three stations were split with a focus on the water, then food, and ending with the waste station. Due to starting so early, little emphasis was placed on the parallelization of prototyping since the team wanted to ensure the circuits were correct and designed well.

With respect to the physical construction of each station, there is too much to comprehensively document. Both the food and water station required extensive 3D printing which was done throughout the entirety of Senior Design 2. A rapid prototyping approach was taken for core 3D printed components, such as the auger for the food station. The housings did not require additional 3D printing. However, small additions such as lids, supports, and standoffs were printed to create strong mechanical connections.

13.4.3 Testing

Firmware, API, and user application testing has been addressed in another chapter. Although much of the component characterization has been discussed in Chapter 10, the following section will be focused on the test plan which was used throughout the hardware. In general, a block and system level approach was taken. The water station may be broken into blocks such as the level sensor, the pump controller, the load cell, and the ESP8266. Throughout Senior Design 1 the blocks were tested and integrated into Senior Design 2. Examples of such testing included breadboarding the optocoupler, pump, N-channel MOSFET and applying a voltage from the power supply emulating a GPIO on the ESP. For the level sensor, external power was applied and the signal on the output pin was measured on the oscilloscope.

The first of the systems to be developed was the Power board. This was ordered and populated by the end of Senior Design 1. The testing of this component started with providing power to the PCB via a digital power supply to ensure the power seen by the input of the PCB, outputs the correct levels using the testing equipment provided in the SD lab. Once established secondary testing included the AC/DC power supply to ensure the correct component is compatible with the PCB and ensure consistency. Fortunately for the team, the first attempt at the design and surface mount soldering proved to be a successful first attempt since the correct voltage levels were produced at test point designed in the circuit, but additionally, as an output shown across a digital load.

For the water station, development on a breadboard enabled the team to begin measurement testing on the load cell to detect minute changes in quantity in the water bowl (refer to Chapter 10.1 for more detail). A number of problems were found during this step, like the load cell read data that consistently started at negative values. This was resolved, with realizing the correct orientation of the component, however, this lead to new bugs, like calibration of the loadcell and dropping negative values if the data jumps between extremes. Additionally, a longevity test was done to ensure that errors in drift measurements did not exceed an allowable measurement. This is important because of the dispensed food could potentially be on the tray the entire day, resulting in some nominal stress applied to the strain gauge style load cell, as discussed in Chapter 3.2.1. Once the bugs for the loadcell and the firmware integration provided consistent results, a test of the pump integration with the prototype was conducted. The tests began with several readings of the pump dispensing from empty to full over differing speeds to determine if deviations in performance could be measured, as mentioned in Chapter 10.2. Fortunately, throughout the design and testing of the PCB, once populated with the core components, the initial design proved stable enough to incorporate a more robust form of testing. To ensure robustness, multiple dispensing tests were carried out to ensure the pump does not burn out after repeated uses, and the loadcell readouts are consistent with actual values when compared to an array of different weights from a standard weights kit. These tests revealed that the quantity measured by the load cell which was dispensed by the pump, were indeed reflected on the terminal.

The approach taken for the Food Station involved a better defined system by considering the successes and failures of the previous prototypes mentioned. Although a scale was needed for the Food Station as well, rigorous testing of this component was not done since its development proved successful. However, testing of the load cell was done to ensure a duplicate system was correctly developed. As with the Water Station, a modularized approach was taken to ensure that problems did not arise down the road. The biggest hurdle the team faced included the realization of the stepper driver and stepper motor integration. These components had its setbacks, which ultimately forced two redesigns of the PCB involving different components when it was discovered the driver did not integrate well with the motor and the motor could not adequately produce enough torque at lower frequencies to drive the food augur as initially planned. Once a working prototype was developed, a finalized PCB was redesigned and sent to be manufactured so testing could be done in the late weeks of February.

The next subsystem, the waste station, did not require the development of a PCB since it was a simple controller with two sensors as peripherals. Its development was the last to be achieved since it was the least hardware concentrated system of the main subsystems. Like the previous subsystems, the waste station was tested in a similar manner, prototyping on a breadboard then transferred to a perfboard for structural integrity. The main concerns of the realization of this system included the humidity sensor since this was a device that hadn't fully been tested and the limits of its capabilities weren't fully explored. It appropriately measured moisture in the immediate vicinity of the sensor, however it is unknown if the sensor could reliably measure the moisture at a max distance as advertised. The test conducted proved contrary to these claims, leading the team to believe the correct testing being carried out on the sensor was not reliable. The last concern included the testing of the sensors that produce an optical beam which detects the presence of a cat. The implementation of custom firmware ensures that false-positives do not occur as well as the implementation of debouncing algorithms ensure repeated triggerings are not accepted.

Finally, the base station, is a subsystem that requires no additional design elements other than what is realized on a software level of abstraction. The main role of the base station is to provide a window into the data recorded by each subsystem, which in turn provides heuristic data the user can understand. The testing of this subsystem was repeated at every cross roads with each subsystem's final testing. It was important that once each subsystem achieved self-automation, communication between base station and the subsystem in question could accurately and reliably reflect data being measured.

13.5 PCB Vendors

Two PCB vendors were under consideration for manufacturing the various PCBs. The following sections will describe why JCLPCB was chosen. The key factors affecting this decision were the board size, quantity of boards, shipping cost, assembly services, assembly cost, and promotions. The two board houses are nearly identical in factors such as board material, number of layers, layer thickness, and more. Hence, the comparison is focused on the cost and convenience of the additional services. The two following paragraphs will describe the various services and expectations from using each board house.

PCBWay has many attractive services and ongoing promotions for new members. On their website they promote the manufacturing of 10 boards for $5. While this is twice the number of boards than JCLPCB, the shipping cost is not negligible. For 10 rectangular, two layer, boards with 100 mm dimensions the raw cost of the boards is $5. The delivery date is same-week but at the cost of approximately $25. Attempting to modify the board dimensions away from the 100 mm dimension drastically increases the price. In addition, including services like SMD stencils or assembly will only drive the price up. JLC will also increase the price if we choose to use these services but the reduced shipping cost provides an affordable opportunity for revisions.

JLCPCB has been the go-to board house throughout the bulk of the project. JLC's presence in the electrical engineering community has made them a reputable and well-known company. Their media presence is mentioned because JLC almost always has special offers including 5 boards with $2 shipping and a free assembly fee. This promotion is only one of several currently on their website. Regardless of the PCB quality, the minimal cost presents an incredibly attractive choice for rapid prototype development, and redesigns if necessary. Similar to PCBWay, many of the promotions involve square, 100 mm dimensions with two layer boards. Surprisingly, JLC provides a $55 per square meter price range. If the PCB dimensions does not fit within the 100 mm dimension than increasing the board size is not costly. With respect to cost, JCL provides more flexible shipping options to reduce their standard 2-4 day shipping at approximately $18 to only a few dollars. Services such as PCB assembly and solder mask inclusion would increase the price but the overall board cost will likely be much less than PCBWay. The last point of comparison lies in large number of resources available on JCL's website. It is quick and convenient to get a PCB designed, uploaded, and verified that the parts are in stock.

In short, JCLPCB provides a cost effective and seamless experience. There is no doubt in the team's mind that we will face an issue we cannot solve. Regardless of cost, ensuring the PCB is manufactured correctly, with high quality, and in a timely manner are the utmost concerns. It is believed that JLC is the best option for a project of this relatively small scale.

13.6 Project Roles

The Purrfect Cat Care System project team is comprised of three computer engineering and two electrical engineering students. The project was first divided into subsystems, the feeding station, base station, waste station, and water station. Then each group member was assigned to one of the subsystems. Chapter 8 Figure 24 shows the system block diagram color coded with each of the group members' responsibilities. Because of the size of the base station and the odd number of group members, two group members were assigned to the base station. These assignments did not mean the person would solely work on that subsystem, instead the team decided it was a way to keep the project on track and each member would be responsible for the completion of the tasks associated with the subsystem. The subsystems were further divided into hardware and software/firmware tasks which were then individually assigned based on requested experience with that part. Table 21 shows the division of labor for each subsystem.

System	Task	Team Member	Role
Base Station	Database & Server	Will	Primary
Base Station	Front/Back-end & Embedded	Carla Will	Primary Secondary
Food Station	Hardware	David Michael	Primary Secondary
Food Station	Firmware	Will Michael	Primary Secondary
Water Station	Hardware	Michael Hector	Primary Secondary
Water Station	Firmware	Carla Michael	Primary Secondary
Waste Station	Hardware	Hector Michael	Primary Secondary

Table 21: Project Roles and Responsibilities

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14 User Manual

Components and Features

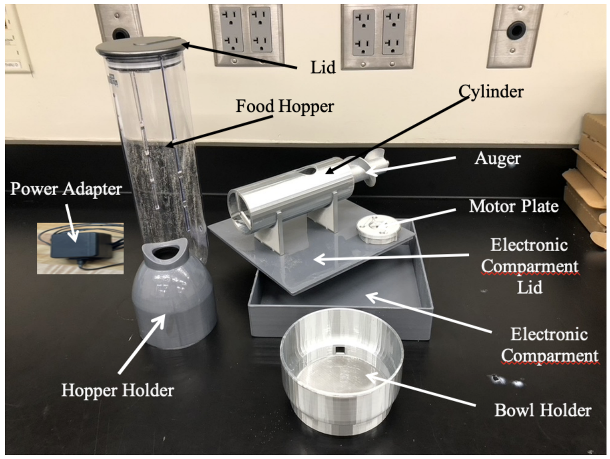

Figure 63: Food Station Components

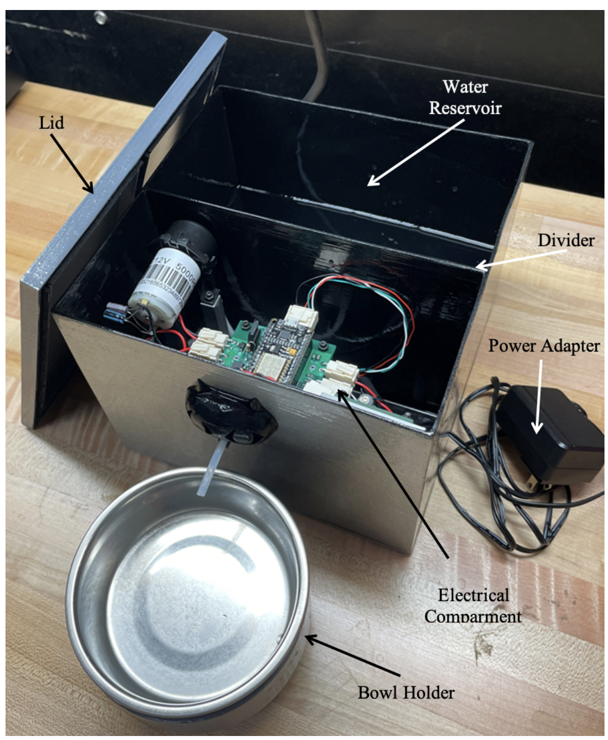

Figure 64: Water Station Components

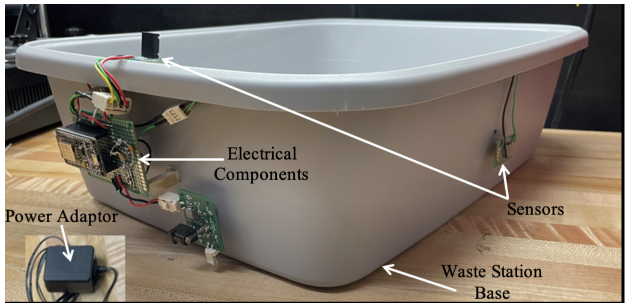

Figure 65: Waste Station Components

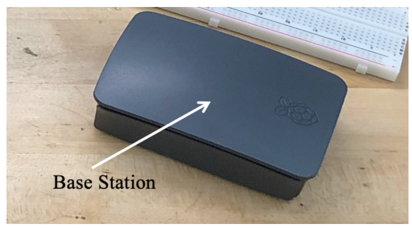

Figure 66: Base Station Components

System Requirements

- A device with access to a Wireless Access Point
- Web Browser that supports Javascript
- Max one cat per system

How the System Works

The Purrfect Cat Care System functionality starts with the base station. The base station is the first system to be powered in-order to established a Local Area Network (LAN) called ”cat care”. Once each sub-system is connected to a power source, the systems will automatically connect to this network. The user will have access to the web-app page ”catcare.com” where they can set the desire schedule for their companion. Once this happens each system will operate according to this schedule.

Setup and Assemble Water Station

1. Remove Lid from the top of the system.
2. If needed, wash and rinse the stainless steel bowl. Once bowl is dry, place on the load cell located inside the bowl holder.

3. Fill reservoir to suggested limit to ensure water tight compartments and replace the lid.
4. The reservoir has a built in feature that will send an alert when the water level reaches below 20 percent of max capacity.
5. Plug in the power adapter. The system will automatically connect to the ”cat care” network where it will receive the desired user schedule and establish communication with the base station to report water consumption throughout the day.

Setup and Assemble Food Station

1. Remove Lid from the top of the hopper.
2. If needed, wash and rinse the stainless steel bowl. Once bowl is dry, place on the load cell located inside the bowl holder.
3. Fill the hopper with your pet’s favorite dry food and replace the lid.
4. Plug in the power adapter. The system will automatically connect to the ”cat care” network where it will receive the desire user schedule and establish communication with the base station to report food consumption throughout the day.

Setup and Assemble Waste Station

1. Plug in the power adapter. The system will automatically connect to the ”cat care” network where it will establish communication with the base station to report the number of usage throughout the day.

Your Purrfect Cat Care System is now ready for use! Use the Smart Web-app to schedule, get notifications and be up to date with your cats food and water consumption throughout the day, week or months.

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15 Summary and Conclusion

When the team began working together to complete a senior design project, they first set out to solve a problem. Although many ideas were discussed, they all found that they shared a common need. That need was the ability to better care for their pet using the very technology they had learned to harness. Although not all team members had a cat at home, they each knew someone who owned a cat and knew how difficult it could be to detect certain ailments in the animal. Due to their nature, cats do not always exhibit any noticeable behaviors that would raise alarm to health issues. Because of this need, the team arrived at the decision to make this their senior design project. Their plan was to design a system that would assist them, and hopefully other cat owners, in identifying when their cat may need more care and attention to their daily habits, and ultimately know if they need to plan a veterinary visit.

After the initial research of existing technologies that could help the team with their design, they then solidified their design requirements and specifications of how they wanted the system to work. After reviewing several industry standards, they also identified any constraints that may affect design decisions along the way. Ther next step was to investigate and decide on the general parts and software components they would need to do further research on to make selections to be part of their final design. Once the parts, software languages and frameworks were selected, this is where the team started developing software and testing each component to make sure they understood how they worked, what their power requirements were, and how they would be connected together so they could include it in their PCB design. Finally, the team developed schematics and ordered their PCB so they could be ready for testing the systems and work toward getting a prototype completed. While all this work was being completed, the team was also recording all of their findings and worked toward creating this senior design I document.

Ultimately, the team gained skills in working together with a team, time management, division of responsibilities and accountability. Although there were some challenges along the way with personal life and school life, the team never gave up and motivated each other to keep going and get the work completed even when the future seemed bleak, all this while balancing their other responsibilities.

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List of Figures

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16 Appendix

This appendix is provided to include proof of permissions for the various photos used throughout this report. Some of the companies contacted did not have an email option. A screenshot of the submitted ticket request is included in place, with relevant personal information omitted.

CatMateC3000.PNG
295 KB

Good Afternoon,

I am a Computer Engineering student at the University of Central Florida, and I am a part of a Senior Design team designing data tracking modules and automatic pet feeders, pet water bowls, and litter boxes. We would like to include one of your images in our project documentation. Our final report will be published on the UCF CECS website after completion (http://www.eecs.ucf.edu/seniordesign/). I am hoping you may be able to help me gain permission for reproduction.

The product we want to mention is the CatMat C3000 pet feeder. We wish to use the last image the websites product page (https://closerpets.com/products/multi-meal-automatic-dry-food-pet-feeder-c3000?_pos=1&_sid=456430836&_ss=r). I have also attached the image since there are several images on the page.

Please let me know if this is possible. If this is not the proper channel to gain permissions, can you please forward this to the proper contact. Thank you in advance!

Regards,
Michael McGarty

Figure 67: CateMate C3000 image reproduction request.

Petmate Fresh Flow II Fountain.PNG
183 KB

Petmate Replendish Feeder With Microban.PNG
166 KB

Good Afternoon,

I am a Computer Engineering student at the University of Central Florida, and I am a part of a Senior Design team designing data tracking modules for automatic pet feeders, pet water bowls, and litter boxes. We would like to include two of your images in our project documentation. Our final report will be published on the UCF CECS website after completion (http://www.eecs.ucf.edu/seniordesign/). I am hoping you may be able to help me gain permission for reproduction.

The products we want to mention is the Fresh Flow II Fountain and the Replendish Feeder with Microban. We wish to use the last image the websites product pages(https://www.petmate.com/petmate-fresh-flow-ii-fountain/product/24817 and https://www.petmate.com/petmate-replendish-feeder-with-microban/product/24477?variantName=color&variantValue=MASON%20SILVER). I have also attached these images since there are several images on each page.

Please let me know if this is possible. If this is not the proper channel to gain permissions, can you please forward this to the proper contact. Thank you in advance!

Regards,
Michael McGarty

Figure 68: Petmate gravity bowl and fountain image reproduction request.

Solids.jpg
119 KB

Installation.JPEG
62 KB

Good Evening,

I am a student at the University of Central Florida and I am on a team of students adding data collection capabilities and automation to cat food bowls, water bowls, and litter boxes for our Senior Design project. We would like to use some of your pictures in our documentation. Our final project documentation will be published on the UCF CECS website after completion (http://www.eecs.ucf.edu/seniordesign). I am hoping you will be able to obtain help be obtain permission to reproduce the attached images. The images were taken from the step 2 gif on the page (https://www.catgenie.com/pages/how-catgenie-works) and from the installation page (https://www.catgenie.com/pages/installation). The purpose of these images is to show how your litter box automate the waste removal process.

Regards,
Michael McGarty

Figure 69: CatGenie sifting and installation image reproduction request.

Good Evening,

I am a student at the University of Central Florida and I am on a team of students adding data collection capabilities and automation to cat food bowls, water bowls, and litter boxes for our Senior Design project. We would like to use some of your pictures in our documentation. Our final project documentation will be published on the UCF CECS website after completion (http://www.eecs.ucf.edu/seniordesign). I am hoping you will be able to obtain help be obtain permission to reproduce on of your product images. The picture is the default image when you go to the ScoopFree original product page (https://store.petsafe.net/scoopfree-original-self-cleaning-litter-box?_ga=2.152505968.874894044.1638759695-1996373607.1638759695). The purpose of these images is to show how your litter box automate the waste removal process.

I hope you can help grant us permissions or point us in the right direction. Thank you for the time and feel free to ask us any questions.

Regards,
Michael McGarty

Figure 70: PetSafe ScoopFree product image reproduction request.