Purrfect Cat Care System

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***Abstract* — This paper presents an improvement to modern automated cat food bowls, water bowls, and litter boxes by implementing data collection capabilities and system integration. The Purrfect cat care system is an automated cat care system that tracks key health statistics and behavior of one's cat. The project presents a mixture of data collection systems and an Internet of Things approach to connectivity. The project was motivated by each group member's negative experiences with current market products for cat care. Throughout this paper the motivation and design of each subsystem, respective specifications, and manufacturing will be presented.**

***Index Terms* — Data Acquisition, Data Visualization, Embedded Software, Internet of Things, Object Oriented Database, Sensor Systems, Wireless Communication.**

I. Introduction

The Purrfect Cat Care System is an autonomous system that offers monitoring and holistic care of a feline companion. The realization of such a system was represented in a modular, four station system comprising a base station, food station, water station, and waste station. The intent of this modularized system was to maintain the flexibility of relocating a subsystem to better accommodate the personality of the feline or the convenience of the pet owner.

In the full system's development, a number of different Standards & Constraints were used in order to develop a prototype that follows IEEE/software conventions and were achievable within the time window set forth by the course. Given these constraints, a set of requirement specifications drove the design of the system by setting parameters that define the abilities that each subsystem may accomplish.

System integration required the implementation of a 802.11 module in order to allow for communication between the base station and the corresponding systems to gather changes in the measurements of food and water consumption or litter box visits. Any updates related to the wellbeing of the feline are reported to the base station at which point is handled by a front end framework called Angular and stored using a NoSQL database.

Finally, the coverage of optimization opportunities are explored in an effort to develop the best product possible. The fabrication of the PCBs required two attempts in order to save on cost of production and time developing a revised board, shipping, resoldering components, and test verification.

II. Standards and Constraints

Arguably the most significant constraints were time and the health and safety of the system. The scope of the project was limited to the year spent across senior design 1 and 2. The group members also had to find time to meet regularly while maintaining a job and other school work. Within this limited time an emphasis was placed on ensuring the cat would be safe. The electro-mechanical and optical systems were designed to keep moving parts away from the cat and electromagnetic components within safe exposure limits in mind. The last constraint is maintainability. The team utilized common components so that the parts used in the project would not become obsolete before its completion, with the realization that components are commonly replaced and taken out of the market.

III. Water Station

The motivation behind the design of the water station was to keep the water bowl full to keep the cat hydrated and track the amount consumed. Dehydration in cats can result in chronic kidney disease (CKD) which may manifest in behavioral changes [3]. The water station monitors the drinking behavior of the cat and records it into a database where the data can be used to decide if a vet appointment should be considered, or aid a veterinarian to better understand the lifestyle of the cat. As a result, the most important sensor used throughout the Purrfect Cat Care system is the load cell.

The development of the water station required a number of different adjustments since this was the first subsystem that was completed. In its design, a 3-D printed housing was developed, which is composed of a water reservoir, capable of holding three liters, a compartment for the PCB, and a water bowl capable of holding 200 mL. The housing provided an enclosure that was convenient for storing the main electrical components like the ESP8266, load cell, load cell amplifier, water pump, water level sensor and optocoupler.

In its entirety, the aforementioned components had to accommodate the requirement specifications initially set for the project in order to attain a realizable goal. The primary requirement specifications that drove the direction of this subsystem may be found in Fig. 1. Regarding the power draw and power supply efficiency, the water pump is the least power demanding motor. As a result, power related specs have been found to meet these specs for both the food station and water station. The details of how the rest of the components meet these specifications are discussed in the respective component sections.

Specification	**Value**	**Purpose**
Max Dispense Time	180 sec	Upper limit restrict wait times
Max Weight Sensor Error	10 grams	Ensures accurate data
Max Average power draw	15 watts	Lowers cost of power
Min. Power Supply Eff.	75%	Reduces energy waste

Fig. 1 Water Station Requirement Specifications

A. Microcontroller

The selection of the ESP8266 by Espressif Systems has a significant impact on the design of the system in that if offers the feature of an integrated WiFi antenna. This module accommodates the fulfillment of making each subsystem modular and was included in the design of the subsequent stations to maintain communication with the base station. This cuts down on space and time designing a separate module that adds to a layer of complexity. It is a microcontroller based on the ESP-12 module and supports IoT based applications. The specs offered by this selection offer the familiar pins of a 3.3V output, an input of 5V, clock speed of 80 MHz, a built-in WiFi stack, supports SPI and I2C, and an appropriate amount of GPIO pins that enable the features necessary to realize each subsystem. It is notable to mention that this particular microcontroller does offer features that are beyond the scope of the project, however the 80MHz clock coupled with the built-in WiFi module offer the necessary convenience of modularization.

B. Load Cell

The sensor selected for the water and food stations is the TAL220B. It is a five kilogram parallel-beam load cell from HTC Sensor, which has the ability to measure small changes in the load on a scale within hundredths of a gram accurately, and maintain minimal drift due to its prolonged sensor deformation. The TAL220B uses strain gauge sensors arranged in a Wheatstone bridge structure. This structure enables two of the sensors to be in tension or compression at the same time. The combination of tension and compression within the bridge allows for the output voltage to be presented as a differential voltage. An excitation voltage of 3.3 volts is applied across the bridge and a differential voltage is taken on the output lines [1]. As a result, the change in voltage potential across one end of the output in relation to the other can be detected. This variation suggests that at a given deformation value, a voltage potential difference will exist. When no force is applied, there is no deformation and, as a result, no variation in voltage potential, resulting in a differential output of zero.

Since the load cell is a crucial sensor in the design process, the chosen load cell was calibrated and tested for both the food and water station under two conditions which utilized a certified set of weights ranging from no load to 1 kg and performing a drift test using 500 g over 24 hours. The first test of no load to 1 kg yield an average value of 0.6% error, an average absolute error of 0.37 g, and an maximum absolute error of 0.98 g. This means after 12 tests, our load cell readings never exceeded more than a gram of error. The final testing included a drift test that was performed over a 24 hour period. In an effort to determine the drift, an initial measurement was taken with a weight of 500 g and left for 24 hours where the final measurement was taken. It was determined that the measurements revealed a negligible value, which easily meets the max weight sensor error.

C. Load Cell Amplifier

The Texas Instruments® ADS1231® 24-bit Analog to Digital Converter for Bridge Circuits Fig. 2 was used to condition and digitize the load cell’s millivolt differential output voltage . The greatest differential output of a load cell with a 1 mV/V rated output under a 5 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. For lower excitation voltage the resolution decreases further. Due to this limited range, and the non-trivial task of detecting µV variations, a preamplifier and ADC integrated circuit were necessary to condition and digitize the load cell’s output.

D. Water Pump

The water pump used to fill the water bowl must meet the following requirements: it must be food-grade, capable of working in dry conditions, and must dispense water within the parameters presented in Fig. 1. The AE1207 from GikFun® offers moderately-low power consumption, low flow rate and compactness. The low flow rate is desirable since cats generally drink 260 mL of water on average per day [2]. The pump operates from 5-15 V with a typical 250 mA current draw at 12 V, the voltage at which the system will be operating.

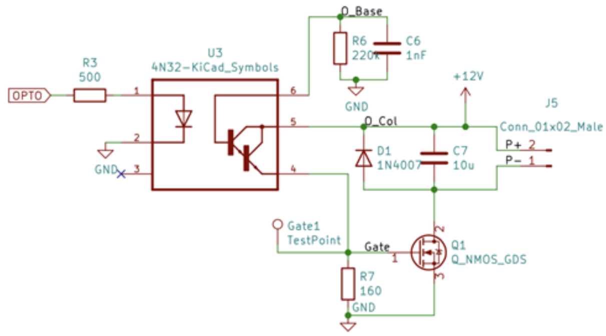

Fig. 2 Water Pump Control

The testing of the water pump requirement specification included use of the load cell to show an increase in the weight as the water was dispensed over time and underwent at least 10 separate tests. The test required firmware to reflect the measurement of the change in weight in the water bowl that would be taken and compared with a programmed threshold value, which would suspend operation of the pump. The test revealed that under no load to max capacity, the water bowl was filled just under 170 seconds on average.

The final requirement specification included the testing of the average power draw and power efficiency of the board. Since the pump requires a 12 V rail to power, and our power adapter is a AC/DC 12 V output line, the testing of this line was not considered since the power output would be 100%. The 5 V rail on the other hand was necessary due to the circuitry involved to power the rest of the PCB during operation. The current drawn to the board, in the absence of the 12 V rail, was 88.5 mA which equates to an average power input of 504 mW and average power consumption of 440 mW. This data reveals an average power efficiency of 87%.

It is noteworthy to mention the 12 V rail and motor is separated from the ESP8266 using an optocoupler (ISOCOM 4N32) shown in Fig. 2.

E. Fluid Level Sensor

As a secondary feature in the water station design was the ability to notify the user of low water levels in the reservoir. To fulfill this task, an optical level sensor provided the ideal specs necessary to accommodate this task. The FR-IR02 Optical Digital Range sensor Fig. 3 was chosen primarily because it is constructed from Polysulanoe, a food-grade material, the simple digital interface, and reasonable price. The Optical Level Switch is composed of an LED and a phototransistor. Since these relatively small sensors are solid-state, it makes them excellent switches for monitoring the water levels of the reservoir.

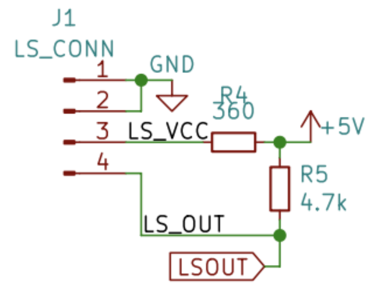

Fig. 3 Level Sensor Interface

IV. Food Station

The realization of the Food Station maintains minor deviations from the Water Station. For the sake of brevity, discussion of the load cell, ESP8266, and the ADC will be omitted since much of the circuitry and component choices remain identical to the Water Station design. The intent of the overall design of the food station is to meet the requirement specifications set forth in the initial drafting of the project also listed in Fig. 4. These specifications offer tangible features the subsystem can offer within a window that is both convenient and realistic.

In the fulfillment of these specifications, the component choices of the motor, driver, and arrangement of circuitry justify the appropriate features. These component choices are the implementation of a 0.6A Hybrid bipolar stepper motor by LIN Engineering®, the addition of the A4988 driver carrier board from Pololu® to moderate the current flowing through the stators of the motor, and a simple 3.3 V to 5 V inverter circuit to convert between the 3.3 V and 5 V domain.

Specification	Value	Purpose
Max Dispense Time	180 sec	Upper limit restrict wait times
Max Weight Sensor Error	10 grams	Ensures accurate data
Max Average power draw	15 watts	Lowers cost of power
Min. Power Supply Eff.	75%	Reduces energy waste

Fig. 4. Food Station Requirement Specifications

A. Dispensing Mechanism

The implementation of the bipolar hybrid stepper motor by Lin Engineering is a notable deviation from the Water Station design since it is essentially an energy sink. The component choice of selecting this motor as opposed to a brushless DC motor involves the flexibility of controlling the rotations of the food augur more precisely. Furthermore, the feature of maintaining a holding torque on the food augur offers an additional layer of control that is not otherwise offered by the DC motor counterpart. The biggest disadvantage of using a stepper motor, is the requirement of implementing a driver circuit to maintain consistent current through the stators of the motor in a precise and alternating manner. For this reason, the A4988 driver carrier board supplied by Pololu fulfills this requirement effortlessly.

The choice of the A4988 driver carrier board offers a straightforward design, as opposed to previous iterations attempted in the design of the Food Station. It utilizes two N-channel full-bridge DMOS FETs which can be controlled by a PWM signal provided by the ESP8266. The driver board is configured to operate in a full-step configuration, meaning that every subsequent step advances 0.9 degrees. Under this configuration, the stepper motor phases 1 and 2 have a home position of 70% of $I_{TripMax}$, which should not exceed an input current of 0.6 A due to the max input current tolerance of the stators. Such a configuration indicates that when phase 1 is at 70% of $I_{TripMax}$ the current through the corresponding stators are in a decay state, while phase 2 at 70% of $I_{TripMax}$ approaches $I_{TripMax}$. The sequence repeats until the enable pin is set high, which in turn suspends the FET outputs.

To verify the specifications of the dispensing mechanism provided in Fig. 4, a brief test dispensing finite amounts of food was done. Utilizing common cat food, the station was able to deliver 100 grams within 45 seconds. During this test the food hopper was filled with 300 grams of kitten-sized kibble to test the dispensing functionality. The dispensing is implemented by an augur, a screw-like shape, which spins counter-clockwise. The rotation motion pushes against the food resulting in a net motion along the auger. The dispensing is implemented electrically using a series of pulses that turn the augur counter-clockwise for 500 ms, followed by 100 ms clockwise, and 100 ms counter-clockwise. The alternating rotation is repeated five times before stopping to take a measure from the ADC to verify the dispensing target weight has been met. The alternating motion also allows for food stuck within the auger to be freed in a timely manner.

When compared with the table in Fig. 4, the dispensing time is far below the maximum time stated in the specification. The specifications regarding the weight sensor error operate in the same way as the Water Station and will mirror the same specs. Finally, the concern for power efficiency demands an average power draw of 15 W and 75% power efficiency. The intent for setting the specification for the average power draw to be 15 W was to yield a realistic goal and offer an affordable operation for the user. This specification was tested by measuring the current through a 12 V rail from the power supply to the station. In doing so, this simplified the calculations since the net current from the power supply represents the near-full current draw of the full system. Therefore, the following data is useful in approximating the power performance of the food station during the operation of the motor, ESP, ADC, and load cell. It will be mentioned later, but the 12 V rail is converted into all other voltage rails.

The station was tested under two conditions: slow and fast motor speeds. The slow test included a 300 Hz square wave being sent to the motor driver, and the net current draw of 1.07 A was observed. In the second test, a net current draw of 0.718 A was observed. After calculations were made, the average power draw came out to be around 13 W and 8.85 W respectively. The average power efficiency, was found in the absence of the 12V rail since the efficiency delivered to the motor is roughly 100%. As a result, the calculation involved the output power over the input power with respect to the power board, which yielded roughly 80-90%. Given these findings, preliminary tests reveal that the performance of the PCB falls within the requirement specifications found in Fig. 4.

B. Food Station Schematic

In the development of the Food Station schematic, the circuitry required may be found in Fig. 5. Beginning with the right-hand side header pins of the ESP8266, the 5 V supply voltage (V_{in}) is accompanied by two shunt capacitors. The pin of the 3.3 V output of the controller operates as the input to the ADC and load cell circuitry. The left-hand side header pins utilize GPIO4, 5, 12, 14, and 15. GPIO15 outputs the 3.3 V step signal to the stepper motor. GPIO12 and 14 maintain the digital out signal and the serial clock that are received from the ADC and load cell, which are sent to the Base Station for recording. Finally the last two pins of the ESP8266 header pins, include the direction pin (GPOI4) and the sleep pin (GPIO5), which grant control of the rotor direction and low power mode operation for the A4988.

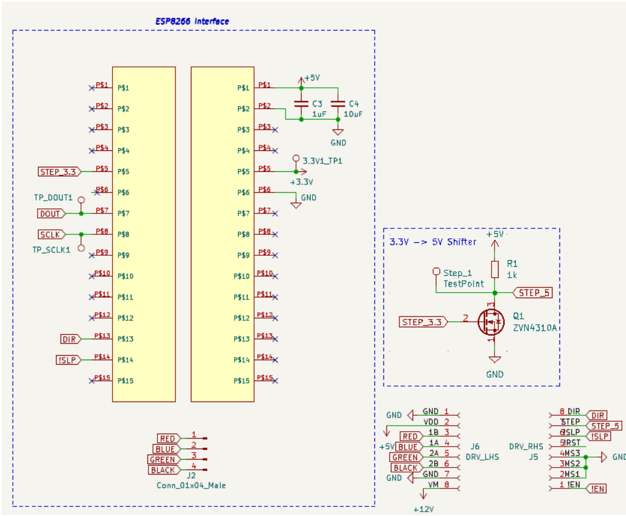

Fig. 5 Food Station Schematic

As mentioned earlier, GPIO15 serves as the 3.3 V step signal that is supplied to the step pin (V_{DD}) of the A4988 carrier board. The A4988 operates optimally with a V_{DD} of 5 V. However, the GPIOs of the ESP8266 are restricted to 3.3 V. These two voltage domains implied it was necessary to verify the ESP could properly communicate with the A4988. From the datasheet of the A4988, the logical high is set by $0.7 \cdot V_{DD}$; 3.5 V. The solution to this problem utilizes an nMOS inverter. The 3.3 V signal from the ESP8266 drives the switching of 5 V on the output node. The signal from the ESP8266 is a 300-600 Hz, square wave. The low frequency implies bandwidth and speed concerns are negligible. The current throughout the inverter is low. The 1 kΩ limits the no-load current to 5 mA which is within the current limit of a GPIO on the ESP. The lack of excessive non-idealities drove the choice of a custom level shifter instead of sourcing a traditional level shifter.

V. Waste Station

The waste station consists of the last data collection module of the Purrfect Cat Care system. Cats, unlike other animals, have the freedom to relieve waste at their leisure. It is this freedom that makes it difficult for pet owner's to notice variations in their cat's waste habits. Variations in an animal's waste habits, is often an early indicator for kidney disease and other common diseases [3]. Thus, the waste station is designed to monitor a cat's waste behavior by tracking the number of times the cat enters the litter box, and by determining whether the cat urinated or defecated.

Specification	Value	Purpose
Detection Distance	1 Meter	Accommodate many widths of litter boxes.
Cleaning Alert Frequency	1 Week	Reminds users to clean the litter box weekly.

Fig. 6 Waste Station Requirement Specifications

The waste station is the simplest of the substations. An ambitious, all-in-one system featuring a custom designed waste management system would be preferable. However, to meet the team's time constraints the system focuses purely on data collection. To track the cat's waste behavior the system is composed of three core blocks: microcontroller, proximity sensor, and a temperature & humidity sensor. These three blocks will compose a small module that is attached to traditional litter boxes adding the tracking features. The system was designed to meet the specifications listed in Fig. 6. The microcontroller will not be referenced since the same ESP8266 mentioned in prior sections was used.

A. Proximity Sensor

The purpose of the proximity sensor is to detect when the cat enters the litter box. Several mechanisms were considered for object detection such as ultrasonic, laser, and simple optical beams. A simple infrared beam generated by an IR transceiver was ultimately chosen. The team's experience with ultrasonic sensors left much to be desired. Many commonly available modules are inaccurate, limited in distance, and more dependent on geometry. A laser implementation would improve on the simple optical beam of the transceiver but would require additional circuitry, thus increasing complexity. The chosen IR transceiver requires minimal circuitry and easily interfaces with a microcontroller for detection.

The TSAL4400 and TSSP40 from Vishay Semiconductors® were chosen to implement the transceiver. The pair was chosen because of their low supply voltage, ambient light filter, 2 meter maximum detection, and significant irradiance. Each of these properties provided maximum flexibility in placing the detector on the litter box.

The chosen transceiver is used commonly in television remote-controls which use 38 kHz modulation. To mimic the data being sent to the transmitter, a 555 timer operating as an astable oscillator was designed. The implementation provided in Fig. 7 produces a 38 kHz square wave. The SE555P from Texas Instruments supports a maximum output current of 200 mA, which is well below the operating point of the IR diode.

B. Temperature and Humidity Sensor

The temperature and humidity sensor introduce the ability to differentiate between urine and excrement. When a cat urinates the relative humidity within the litter box typically increases. If the measured humidity were to increase above some heuristic threshold it is likely the cat urinated. Inversely, if the cat entered the box for a significant period and the humidity did not increase it is inferred the cat defecated.

Given the current waste station design, a number of major flaws exist that prevent optimized operation. If the cat enters the litter box for a significant time and does not release waste a false-positive will occur. The aim of this feature is to try and provide relative data regarding waste (e.g., if a cat began to urinate more than usual, this trend would be presented to the user). To assist in the pet's health evaluation, this information regarding the cat urinating more often than normal can be provided to any veterinarian. The simplicity provides many advantages over any additional detection schemes which could be used.

C. Waste Station Schematic

Shown in the schematic for the waste station in Fig. 7, a 0.01 µF capacitor was chosen to simplify the resistor design. The following formulas provided in the SE555P's datasheet were used to determine resistor values

$$t_h = \ln(2) R_4 C \quad (1)$$

and

$$t_l = \ln(2) R_5 C. \quad (2)$$

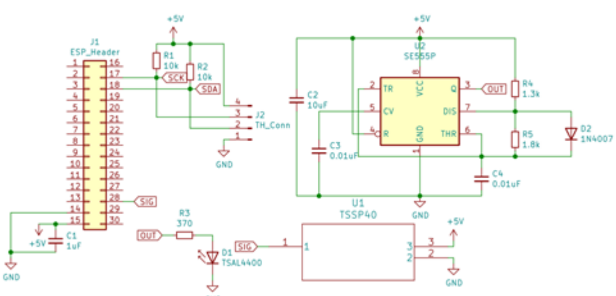

Fig. 7 Waste Station Schematic

Ideally, the resistor values for R4 and R5 will be equal. However, prototyping was done with a 1N4007 diode as opposed to a more appropriate 1N4148 signal diode. The 1N4007 diode was readily available to us, although an 1N4148 would have been preferable. The forward curve for the two diodes differ, resulting in a non-negligible equivalent resistance while both diodes are forward biased. To account for the discrepancy the R5 resistor was increased to 1.8 kΩ to force the duty to 50% and to tune the frequency to 38 kHz.

The IR transmitter utilizes a 370 Ω series resistor to place the diode's operating point at an approximate 10 mA draw, forward voltage of 1.25 V, and an irradiance of 4 mW/sr. This operating point is sufficient to meet the required 2 meter detection distance.

VI. BASE STATION

From a hardware perspective the base station does not require any design. A development board such as the Raspberry Pi model 3 was purchased to host the user interface, server implementation, and database. 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; no additional hardware components were designed for this station.

VII. SOFTWARE

Keeping the project goals in mind, the base station was designed to provide cat owners a reliable, easy, and completely automatic way to track their cat's health. Using the data provided by the sensors on each of the substations, the base station can monitor a cat's eating, drinking and litter behaviors. This monitoring data can be displayed to the user through an easy to use, wireless application.

The reliability of the system depends on each of the subsystems' ability to run independently of the base station and of one another. Specifically, upon startup, each system will automatically run an initialization procedure to connect to the base station and begin to report their data. On the base station, the web server will automatically start up and begin serving the frontend, API, and database on a WLAN which will be broadcast to the user to connect to through their computing device.

Once the systems are initialized, each system will begin autonomously to complete their given tasks. The water station will always keep the water bowl full and monitor the remaining reservoir level to alert the user if it ever becomes low. The water and food stations will communicate wirelessly with the base station to report the total amount of consumption for each day and the waste station will report the total litter box usage. The data will be tracked and displayed on the frontend.

A. Frameworks

The frontend was designed to be intuitive and easy to use. The framework selected to design the frontend was Angular, which is a framework that is coded in TypeScript in an IDE and generates JavaScript code when compiled. Using TypeScript requires more effort up front but reduces the amount of time used to debug errors. Also, Angular has a focus on being compartmentalized into components that can be reused, making it easy to move them around and design the site in a logical manner. Finally, the libraries included in Angular allow for faster calls to the backend allowing the frequent data updates from the substations to be displayed immediately.

NodeJS was used to serve the middleware API (Application Programming Interface) which is written in JavaScript. The API provides all the endpoints, functions, for the frontend and the substations to communicate with the base station. NodeJS uses NPM, a command line tool, to make it simple to create, build, and deploy the server.

The data received from the substations will be stored and managed in a MongoDB database hosted on the base station. MongoDB is a non-relational database which stores data in structures called documents. The format used for the documents is JSON (JavaScript Object Notation) which is easy to work with and matches the format used by JavaScript. The objects make querying fast making it easy to display the updated data in real time to the frontend.

B. Features

The frontend is hosted locally on the base station and can be accessed by the user by connecting to the base station first and then accessing the Purrfect Cat Care site at catcare.com. The frontend dashboard contains the current data received from each of the substations which will be displayed as the data is updated in real time. All alerts from the system will be displayed on the dashboard in order of most recent with the option to view the alert details and delete the alert once the user has reviewed it. Alerts to the user will include cat behavior changes such as any outliers calculated in substations' data, and system related alerts such as low water reservoir levels. Also available on the dashboard is the ability to manage the feeding schedule which will be used to dispense the food in the food station.

The frontend's second page is the statistics page where the user can view the data received from each of the substations with the option to view one week, month or years' worth of data if available. The first tab displays the overall statistics including mean, standard deviation and total values. The second and third tabs display the daily behavior data as graphs so the user can view the data visually.

C. Database Design

The database was designed to organize the data in a simplified manner so that less data processing would be needed on the API or frontend layers. The database contains collections for the food, water, waste, alerts, and schedule data. Timestamps are used for the sensor data for easy sorting and filtering. Month and day are included in the sensor data collections for identification and displaying on the frontend. The water and food station data will only have one entry per day as the stations report cumulative consumption information. The waste station will have multiple entries as the station will report into the base station each time the RF sensor is triggered. The schedule collection will contain only one entry for a schedule of 5 different feeding times in an array. To avoid cluttering the dashboard, the alerts of the same type will be overwritten. For example, if the water reservoir is low, the station will continue to send alerts until the reservoir has been refilled, but only the latest alert will be displayed on the dashboard.

D. Firmware Design

Embedded firmware for each substation was developed. The major goal of the firmware is to be reliable and autonomous. Early on, the design involved a central controller running on the base station to direct each substation's actions. However, it was determined that this setup would introduce a major single point of failure. If the base station stopped running, all of the cat's care systems would also stop functioning and collecting data. Therefore, it made more sense to move the bulk of the logic to the firmware itself, and to decouple its behavior as much as possible from the base station. With the current design, each subsystem is capable of acting completely independently, not only of the base station, but also of each other. This allows major firmware changes to be made without worrying about breaking the base station, and would also allow new substations to be easily added in the future, with only minor changes to the base station.

A number of specifications relating to measurement accuracy and food and water dispense time are directly dependent on the design of the firmware. For example, the motor and pump on the food and water stations respectively are carefully controlled to meet the specification of 180 second dispense time maximum. In addition, ADC is directly controlled to ensure the highest accuracy possible, so the value is within ±5% error of the maximum scale weight (5 kg.)

The firmware must control a variety of sensors and peripheral devices. Many of the devices present simple "on-off" interfaces which can be controlled with single GPIO pins. However, the load cell ADC and stepper motor driver required more sophisticated software to be developed.

The load cell ADC uses an unusual SPI-like interface, which requires a custom implementation of SPI by manually controlling the GPIO pins. In particular, the MISO pin is monitored for a low pulse from the ADC, indicating data is ready, and then sent 25 pulses on the clock line to shift 24 bits in and then the state of the ADC is reset. Implementing this manually was necessary because of the need to poll the MISO line without any clock pulse, and to send exactly 25 clock pulses to properly fetch the reading from the ADC.

The stepper motor driver requires a PWM signal to indicate when a step should be taken. Since the steps are based on each edge, the speed of the motor is controlled by changing the frequency of the signal.

To save power, the microcontroller enters low power mode between updates. The ESP8266 has three different levels of low power mode, and the most power efficient one is used because short wake-up time is not a priority for this project. In addition, the stepper motor driver is put into sleep mode when it isn't being used, otherwise it draws nearly half an amp when idle. In sleep mode, it draws less than 1 milliamp. These two strategies combined, keep the overall power consumption relatively low.

In the event that the firmware encounters a situation that it can't handle, such as the water reservoir being empty, or food not dispensing due to a foreign object, it will send an alert to the base station. These alerts are a request to the user for help, but the substations will continue to try to operate as normal.

E. API and Firmware-Communication

The firmware needs to report data and alerts to be stored in the base station's backend, and retrieve information about the feeding schedule and time of day. The frontend needs to retrieve data and resolve alerts, and set the feeding schedule based on user input. To handle these requirements, the API connects the firmware, frontend, and backend together.

The API uses HTTP with JSON to transfer data. This way, API requests can be made over reliable connections using existing technology, such as requests from a web browser, and the ESP8266's provided HTTP library.

To keep the interface between the base station and firmware simple, and to keep the firmware autonomous, all information that the firmware wants from the API has to be explicitly requested. This completely removes the need for the firmware to actively listen on an open port, and also removes the need for the firmware to need static IP addresses for the base station to contact. It also makes the base station more agnostic to the kind and number of substations that are querying it and providing it information. Any future additions to the kind of substations the base station supports would only require new API endpoints, and an update to the frontend to show any new collected information.

F. Base Station Configuration

In order to provide connectivity between all the stations and an interface, the base station provides its own 802.11 wireless access point. The base station acts as a DNS server, DHCP server, and web server.

Hostapd (host access point daemon) is used to configure the base stations network interface as an access point and it also controls the wireless SSID and authentication. However, it does not assign IP addresses to new hosts or resolve addresses, since it operates at a lower layer of the TCP/IP stack.

To provide DNS and DHCP services, dnsmasq is used. Dnsmasq listens on the base station's port 67 for incoming requests and automatically assigns new hosts IP addresses. Dnsmasq also listens on port 53 and acts as a DNS server.

Using this setup, the base station can be isolated from the global internet, and provide the user with a personal local data storage. All the user has to do after they put the system in place, is connect to the local "Catcare" WLAN, and enter the address "catcare.com" into their web browser. This is possible because any name needed can be assigned to any IP address.

Putting the base station on its own WLAN and configuring it with a static IP address, ensures that the firmware has a simple way to contact the base station, and in fact the address of the base station can be hardcoded in the firmware.

This setup also doesn't require hosting on any dedicated servers on the internet, which reduces the cost needed to operate the system. A global user authentication system also isn't necessary, since the authentication is done by being in proximity to the Cat Care system and knowing the provided password for the WLAN.

Another concern for the base station was keeping accurate time. Because the base station does not have access to time servers, a real time clock was integrated into the final design. The RTC module connects to the base station via the I2C protocol. During assembly, the correct time is set from an internet time server, then that time is set in the RTC. With an onboard lithium cell battery, the RTC will keep the correct time even when power is lost.

VIII. Fabrication

The PCB design and 3D printing composed a bulk of the project fabrication. A PCB was designed for both the Food and Water stations. Due to time constraints, the Waste Station is constructed on a prototype board. Two revisions were made to each PCB to address firmware and space optimizations, each of which will be discussed in their respective sections. JLCPCB was used to fabricate three boards and all revisions.

A two-layer board was chosen for each PCB. In general, the green layer represents a ground plane on the bottom layer of the board. Inversely, the red signals represent either signal or external power pours.

A. Power Board

The modular nature of each station presented the choice to either combine the power supply onto each of the PCBs or separate the design onto another board. With a focus on time, the choice was made to separate the power and digital boards for each station. The power supply design Fig. 8 was provided by Texas Instruments' WeBench and layout guidelines provided by the TPS54328 datasheet.

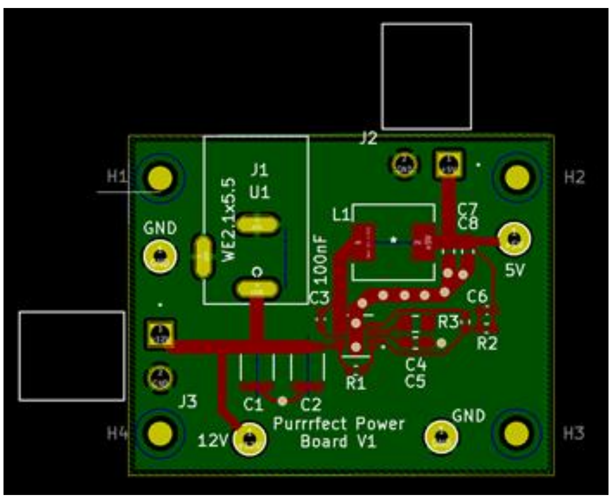

Fig. 8 Power Supply PCB Layout

B. Water Station PCB

The water station PCB Fig. 9 was designed to optimize GPIO usage in firmware, minimize board area, and maximize the distance between power domains. The board is split into three columns corresponding to 5V, 3.3V, and 12V domains; from left-to-right. Several GPIO pins share functionality with the boot, flashing, and internal UART channels. The functionality sharing did not significantly affect the design, but it was decided to assign the GPIOs into unique functioned pins. Area was addressed by moving the ADC and several test points under the ESP and compactly organizing the level sensor and pump sub-blocks.

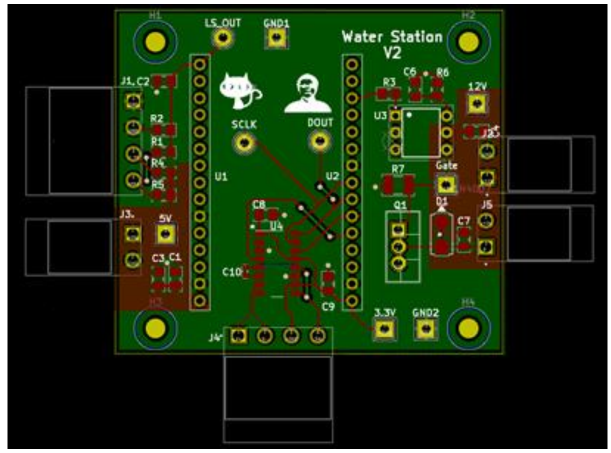

Fig. 9 Water Station PCB Layout

B. Food Station PCB

The Food Station PCB Fig. 10 follows many of the same ideas as the Water station. The first iteration of the Food Station's PCB did not properly utilize the space between the external header pins. For example, the transistor converting a 3.3V square wave to the 5V domain comfortably fits underneath the motor driver. Since the firmware was developed alongside the PCB, further optimizations were made with the wiring of the ADC underneath the ESP. Additional space-saving modifications could be made to the left-hand side of the board. However, the current state of the PCB is sufficient for the final demonstration.

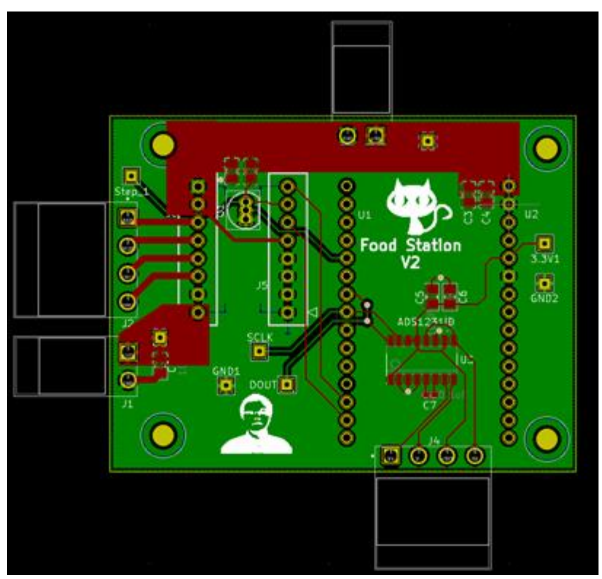

Fig. 10 Food Station PCB Layout

IX. Conclusion

The complete design of the Purrfect Cat Care System underwent a number of revisions in order to accommodate the challenges presented by the COVID-19 silicon shortages and extraneous circumstances that hinder the progress of the project. The project followed a set of standards and constraints that helped drive the direction of how the system may be realized. The modularity of the system enabled the ease of troubleshooting specific problems throughout the project design, which led to pivotal design decisions that allowed on-the-fly revisions to existing schematic errors. The final product successfully demonstrates the requirement specifications previously introduced, which was made possible through the harmonized effort of hardware realization and software implementation.

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