Hope this won't take too Delong: Smart Pet Feeding Station

A Technical Report submitted to the Department of Electrical and Computer Engineering

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

Luke Orioli

Spring, 2022

Technical Project Team Members

Matthew Garrison

William Mulquin

Landon Rhodes

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Harry Powell, Department of Electrical and Computer Engineering

Statement of work:

Matt

For this project I contributed to most areas of the project. Initially, my primary goal was to design the dispensers for the project. This eventually involved determining what motor, motor driver, and pumps would best suit our needs. Once I decided on what parts to get, I helped derive values necessary for components used with the motor, motor driver, and pumps on our PCB. When these parts, and the PCB were finally delivered, I helped with testing them, and wrote all the code necessary to use them. With the code done, I was pretty much done with what was originally established to be my portion of the project.

With my part of the project finished, I began working with my teammates more, especially as we began to run into challenges caused by design oversights, and part malfunctions. I generally supported their efforts, especially in Luke's portion of the project. In particular, I designed the roberval balance part in Solidworks. This part was essential to the functionality of the weight sensor in the project. My final contribution to the project was in helping construct the structure of our device during finals.

Landon

For this project, I was primarily responsible for the parts that relate to the screen and the buttons. Specifically, I researched and selected the LCD character display module for the User Interface. I built a driver library containing some basic functions to interface with the screen according to the instruction table in the datasheet. I designed and programmed a menu for the user interface with many options, pages, and links between pages but unfortunately it didn't make it into the final demo, because we ran out of time before we were able to integrate it into the rest of the project.

Because of my exposure to and familiarity with woodworking projects at home, I was able to construct the main wood frame of the dog feeder from a large piece of plywood. Additionally, when putting the project together, if anything needed to be cut, drilled, or fastened, I made sure that it was done so accurately and securely.

Will

For this project, I was primarily responsible for the 3D design of the rotor and food dispensing mechanisms of the machine. More specifically, I researched similar designs of dispensing mechanisms, similar to candy machines and also a pellet dispensing machine developed by NIH. Our design closely resembled these. I used this research to guide our dimensions, components, and also ensuring that our rotor would not break under the influence of the dog food weight.

Towards the end of the project, I assisted Luke and Landon in designing the final structures of the machine, designing the food reservoir, food chute, and stabilizing the motor driver in place. I also worked on the aesthetic component of the machine, painting parts to ensure the professional component of the device was completed.

Luke

During the beginning of the project, I was responsible for selecting sensors to be used for tracking the food and water in the water bowls, and for designing and implementing the different sensor interfaces for the selected sensors. I designed an instrumentation amplifier interface for the weight sensor, and a voltage divider unity gain buffer interface for the water sensor. I also selected all of the connectors that were needed to connect the external components to the PCB board. After finishing the design for the sensor interfaces, I designed the power circuitry for the project by looking at each major components power requirements and selecting voltage regulators that fit these requirements. From the power requirements, I was able to select an appropriate power converter. Once the schematics for the project were completed, I created the PCB board layout in Ultiboard. More specifically, I created custom footprints for all of the devices, and made all of the necessary connections between them.

I also implemented a large portion of the system software since I created the base program, generated appropriate data structures for each of the component FSM types and created data structures and functions for system dispensing events. I also assisted Landon, Will, and Matt in building the 3D wood model for the device.

Table of Contents

Contents

Table of Figures

Abstract

The Smart Pet Feeding Station is a device that automates the semi-daily process of feeding and watering pets. The device dispenses controlled amounts of dry pet food and water into separate food and water bowls during user specified feeding and watering times. The device also gives pets access to a constant water supply by maintaining a fixed water level within the water bowl. To accomplish these tasks, the system uses a weight sensor and two water level sensors to track the amount of food and water within the bowls. This information is interpreted by a microcontroller, which controls the food and water dispenser motors. Through the completion of this project, the group was able to experience the process of designing and constructing an artifact in a real-world engineering design project.

Background

As all pet owners know, a major responsibility of ownership is providing pets with adequate amounts of food and water throughout the day to ensure that pet health is maintained. For dogs, this means that they should be provided about 1 ounce of water per pound of body weight each day [1], and anywhere from 1/3 cups to 4.5 cups of dog food each day, depending largely on the pet's weight [2]. Although there are several feeding regimens that can be used, one that gives owners the most control over their pet's weight and health is portion controlled feeding, where a fixed amount of food is provided to the pet during specific times of the day [3, p. 136]. This regimen also has the benefit of allowing owners to observe behavioral differences based on their pet's feeding habits to determine possible health issues [2, p. 136], [3].

Although the portion controlled feeding method is effective, it requires that owners spend a greater amount of time planning and preparing meals, time that not all owners have. This is confirmed by a survey carried out by the American Humane Association (2012), which identified time constraints as a major barrier to pet ownership among previous dog and cat owners [4]. Thus, students and employees, who constitute busy pet owners, may have time constraints that inhibit their ability to properly plan and prepare meals for their pets throughout the day. Elderly and disabled pet owners are another group that may have difficulty feeding their pets due to mobility or psychological issues that pose a challenge in the feeding and watering process. To lower the barriers to pet ownership and to ensure that all pet owners are able to keep their pets happy and healthy, a decision was made to automate the feeding and watering processes by developing the Smart Pet Feeding Station.

Automatic pet food and automatic water dispensers are not novel ideas as many versions of these devices exist. For example, WOPET's Chimp II Automatic Cat & Dog Feeder is a Wi-Fi enabled pet feeder that is capable of dispensing up to eight meals a day, twenty portions (5 grams per portion) per meal, and can play 10-second voice recordings to get a pet's attention [5]. A current automatic water dispenser design is PetSafe's Drinkwell Everflow Pet Drinking Fountain, which is a 192 fluid ounce fountain that connects to a standard garden hose, has an adjustable water level, and automatically turns off when the desired water level has been reached [6]. Although similar to current automatic dispenser designs, the Smart Pet Feeding Station is a two-in-one design since the device is capable of dispensing both pet food and water, which is a feature that was not present in any of the currently available automatic dispensers that were found. This means that the dispensing of food and water can be easily synchronized since the same real-time-clock counter is used for both dispensers.

The design and construction of this automatic food and water dispenser required the extensive use of previous coursework. The custom PCB that was built required the use of circuit design principles that were introduced in the Electrical Engineering Fundamentals Series (ECE 2630, ECE 2660, and ECE 3750). Since a MSP430 microcontroller was used to interact with various sensors and actuators, embedded programming knowledge from the Introduction to Embedded Computing Systems (ECE 3430) course was utilized. The sensors, actuators, and microcontroller create feedback loops within the device, thus some of the information introduced in Linear Control Systems (ECE 4850) was helpful in implementing the sensor feedback. Many of the components were interfaced with the microcontroller using instrumentation amplifiers, operational amplifiers, and other RC networks, thus the circuit design principles from the FUN series were very useful in designing these circuits. Since stepper motors and peristaltic pumps were incorporated in the design for the food and water dispenser, concepts from Electromagnetic Energy Conversion (ECE 3250) were used in understanding motor excitation. The power circuitry, which relied on the use of several voltage regulators and conversion of AC power to DC power, used material from both ECE FUN III and EM Energy Conversion. Digital signal processing techniques and knowledge were used in designing the digital averaging filter for the weight sensor and understanding the microcontroller's Analog-to-Digital converter. Finally, the preparation of documents and files for PCB manufacturing used the process introduced in ECE FUN III.

Constraints

Design Constraints

The Smart Pet Feeding Station had several design constraints that directed the final design of the device. First, the project required that a PCB be designed for use in the device, and that a microcontroller be implemented. The MSP430FR2355 microcontroller [7] was selected to be used in the project since the corresponding launchpad for this microcontroller has 44 IO pins [8]. The availability of 44 IO pins also serves as a design constraint on the number of peripheral devices that can be interfaced to the microcontroller. Another design constraint was the software that could be used for the different parts of the project. For creating the device schematics and board layout, it was recommended that Multisim and Ultiboard [9] be used. When designing the PCB for the project, the PCB was limited to two layers and there were several dimensional constraints that had to be followed to ensure that the board could be fabricated. A final design constraint for the design of the device was part availability. Supply shortages and shipping delays required that certain parts be selected over others in the final design. To ensure that parts would be delivered on time, the requirement was imposed that parts ordered from Digikey could not be marketplace items, and parts could not have any back orders.

Economic and Cost Constraints

A budget of $500 was allotted for project expenses, which limited the selection of several components and the device's 3D structure. Although one of the goals of the project was to make a cost-effective automatic dog feeder and waterer, some of the chosen components are more expensive than would have been desired. For example, each of the two OLS5 water sensors costs $43.12, which is not ideal if this device were to be put into production. Fortunately, this constraint was somewhat mitigated since the project incorporates some components from previous capstone projects, which are not presented as costs in this design.

Environmental Impact

The Smart Pet Feeding Station was designed using mostly RoHS components, which minimizes the environmental impact of the device. The disposal of the device may negatively impact the environment if the device is not properly recycled, however the use of RoHS components limits the amount of toxic chemicals that are released into the atmosphere [10]. Another consideration is the impact that the device will have as a result of being powered by the grid. The impact will be dependent on the user's energy supplier, which may negatively affect the environment depending on the type of power plant that is used to generate electricity [11].

Sustainability

The system will be relatively easy to manufacture as most of the components, including the sensors, dispenser motors, LCD screen, buttons, MCU, passive and active circuit elements, and power converter are readily available from online vendors like DigiKey. The two primary constraints that affect the manufacturability of the system are the custom-made PCB that has to be fabricated and the physical structure and mechanical parts in the device, which would be plastic cast in the context of actual manufacturability.

Health and Safety

Since many of the device components operate within close proximity to pets, health and safety was a concern in the development of the smart feeder. One concern is that pets may attempt to get into the device and possibly play with the wires or gain access to the actuators and mechanical assembly for the food and water dispensers. Thus, these parts of the device would have to be inaccessible to pets through the use of partitions and by limiting the size of the food dispenser. Although these measures were not implemented in the project, the consumer version of the product would implement these measures.

Another concern is that the circuitry is in close proximity to water, which can result in shorts or possibly shocks to the pet or user if water is spilled on the electronics. This was partially acknowledged in the project since the water sensor electronics were sealed from water in the water bowl and all exposed portions of wire were covered tightly with tape, however the PCB and other electronics are not contained within separate enclosures, thus there is a risk that water could destroy the PCB.

The ability to clean the device was also considered since food and water can lead to bacterial growth in the machine. The dispensers and pathways that the food and water take should be accessible to the user so that they may clean the device, or the device should be capable of cleaning itself.

External Standards

The device must be protected from exposure to water and solid dog food since these substances are stored and dispensed within the device. Once these substances are poured into their respective bowls, the sensors contained within the bowls must be isolated from the substances and the pet using the bowls. Another concern is the spilling of water on the body of the device. As such, the water bowl and container enclosures should adhere to the NEMA Type 6P standards, which provides a degree of protection against access to hazardous parts, ingress of solid foreign objects, and ingress of water, particularly for prolonged submersion. The remaining enclosures of the system should adhere to the NEMA Type 4 standards, which provides a degree of protection against access to hazardous parts, ingress of solid foreign objects, and ingress of splashed water [12]. Although these standards were not strongly adhered to in the final design of the product, they would certainly be incorporated into the device if the device were to be mass produced. For the design and manufacturing of the custom PCB, the IPC-2221 standards for generic board design [13] and the IPC-2222 standards for organic rigid printed board design [14] were followed. The Barr Standard, which is a standard consisting of a set of rules for C coding that is adopted by a team of programmers when designing an embedded system, were also used when programming the embedded software for the MSP430 [15].

Tools Employed

This project required the implementation of numerous different tools for all aspects of the project. For the design of the PCB, Multisim and UIltiboard [9] were used extensively. To test the parts, and the PCB a National Instruments Test Bench was used [16]. Software for the microcontroller was written using the C programming language in Code Composer Studio [17], and was shared among the group using GitHub [18]. For some aspects of the prototype very specific parts designed to very specific specifications were needed. These parts were all designed in Solidworks [19], and printed using University of Virginia 3D printers. The structure of the prototype itself was constructed of wood, done so using a variety of woodworking tools. Of humorous note, the group member responsible for acquiring hardware for the construction portions of the project attained significant knowledge of Unified Thread Standards, and ISO Metric Screw Thread standards over the course of their several trips to Lowes.

Ethical, Social, and Economic Concerns

One of the ethical concerns is how the device will affect the mental health of pets. Traditionally, pets are fed and given water by their owners, however with the automatic food and water dispenser, pets may receive less interaction with their owner and may be left alone for longer periods of time, which can lead to a host of problems, like loneliness and depression [20]. Another ethical dilemma that could come with entrusting the safety of a pet with an electronic device would be the chance of it failing for some reason. If the device were to fail due to a power outage, external damage, or a design flaw, this could have grave consequences. An additional social and economic concern is the cost of the device, which is over $400 dollars. This device is not affordable for the majority of people, and thus mostly benefits members of society who are in the upper class.

Intellectual Property Issues

[21] is a US patent that automatically dispenses pet food into a bowl using a motorized auger. The food dispensing part of our project is similar to Krishnamurthy's design in that both allow a food tank above to dispense a controlled amount of food into a bowl below using a motorized actuator. Krishnamurthy's main claim involves an augur mounted to the motor inside a mostly enclosing tube, that moves the food between the tank and the bowl. Because our design involves a flat rotor piece with holes instead of an auger as the dispensing agent, it does seem like our design would still be patentable.

[22] is a US patent that attempts to solve a similar problem of feeding a pet automatically at programmable times. It solves this problem by having a circular bowl with pie shaped divisions and a rotatable cover allowing access to only one pie shaped opening at a time. A major difference in functionality between this patent and our system is that we allow the user to program an amount of food to be dispensed, whereas this patent allows the user to scoop the exact amount of food they wish into the correct section. The designer's main claim involves a programmable and removable timer module, a base to hold the timer module, a bowl with pie shaped divisions, a cover over the bowl, a handle to secure the cover, a locking member to secure the cover to timer module, and an RF receiver in timer module for remote control. Every other claim is a further specification and clarification on this main claim. Our design would not interfere with this main claim, because our structure is substantially different from each of these parts with the exception of timer module part, which is too broad of a concept to patent.

[23] is a US Patent that provides a purely mechanical solution to a combined pet feeder and waterer. Willet's design involves an inner food bowl, an outer water bowl around the food bowl, and a tower holding the food and water tanks. This is an on-demand system with no electrical parts at all, where gravity allows the food and water to flow into the appropriate bowls from the tower above, whenever they run low. This would not give the user any control in how much food is dispensed, whereas our design does allow a programmable amount to be dispensed. Willet's main claim is essentially a description of the layouts of the food container, water container, food bowl, water bowl, and base receiver unit, all of which are completely different from our project design.

Detailed Technical Description of Project

The Smart Pet Feeding Station is a device that automatically dispenses fixed amounts of food and water into separate bowls during user specified feeding and watering times. Food and water are stored within the device in separate food and water containers. These substances are transferred to their respective bowls using the food dispenser's stepper motor and the water dispenser's two peristaltic pumps. The device uses multiple sensors embedded in the bowls to actively measure the weight of food and the bowl water level while the substances are being dispensed into the bowls. Using an LCD screen and buttons, the user of the device can create future feeding and watering events. These subsystems are connected and controlled through a microcontroller. The relationships between the different subsystems of the Smart Pet Feeding Station are shown in Figure 1.

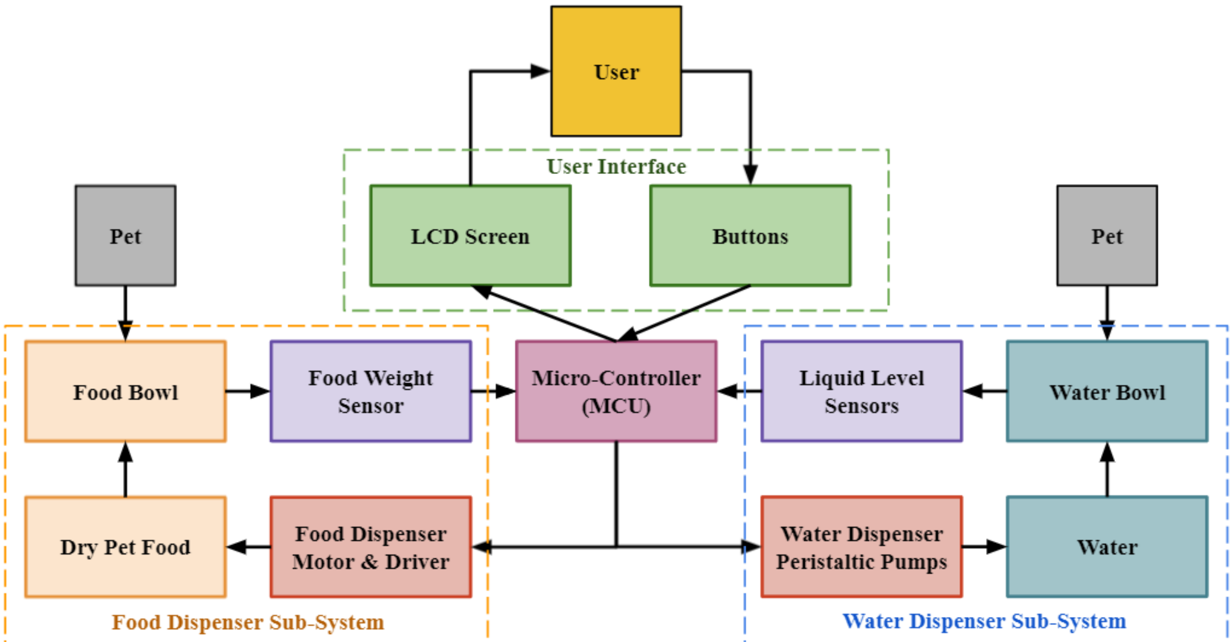

Figure 1 Smart Pet Feeding Station Block Diagram

In the following sections, the design and implementation of the system hardware, software, and physical structure are discussed in detail.

Hardware

The first part of the project was designing the system hardware. The completed schematics are shown in the Appendix in Figure 30 and Figure 31. The board layout is shown in the Appendix in Figure 32 and

Microcontroller Selection

For this project, the MSP430FR2355 microcontroller [7], as part of the MSP430EXP430FR2355 Launchpad development kit [8], was implemented since it contains 44 IO pins, can operate at a high frequency of 24 MHz, contains 12-bit ADC modules for precisely measuring the food bowl weight sensor output, and the MCU contains multiple clocks including a Real Time Clock, which is used to track the time of day in real time. The use of a Launchpad in place of a standalone microcontroller allows the MCU to be easily connected to other hardware using pin headers since the launchpad is itself a printed circuit board with header connectors. The launchpad also comes with a debugger, allowing break points to be placed within the program. As an extension to the launchpad, a custom PCB was fabricated, which sits on top of the launchpad's IO pins.

Weight Sensor Interface

When the device dispenses dry pet food, the amount of food in the food bowl is measured by a load cell weight sensor so that the food dispenser stepper motor can be turned off once a certain weight of food has been reached. The load cell that was used for this project is the FX-1901, which has a pushbutton type actuator and can measure up to 10 pounds of weight [24]. This sensor is internally wired using a Wheatstone bridge architecture, meaning that the sensor has two outputs, the difference of which provides information on the current weight. The datasheet for the sensor shows that the load cell has a maximum full scale output span of 24 mV/V [24], meaning that with 5 Volts of excitation, the sensor's maximum output difference when only 5 pounds of the rated 10 pounds is applied to the sensor is 60 mV.

A weight sensor interface was designed so that the output of the weight sensor could be interpreted by the MSP430's 12-bit Analog-to-Digital Converter (ADC). The interface uses the AD623 instrumentation amplifier to amplify the difference between the weight sensor outputs [25]. Since the MSP430 is supplied with 3.3 V and the instrumentation amplifier is supplied with $V_{CC} = 3.3$ V and $V_{EE} = 0$ V, the amplifier's reference voltage is set to 1.65 V, meaning that the load cell's maximum output difference of 60 mV should correspond to an amplified differential voltage of 1.65 V, which is a gain of $G = 27.5$. The gain resistor R_G was determined using the following equation, which was provided by the AD623's datasheet [25, p. 24].

$$R_G = \frac{100\ \text{k}\Omega}{G - 1} = \frac{100\ \text{k}\Omega}{27.5 - 1} = 3.774\ \text{k}\Omega$$

A common resistor value of $R_G = 3.9\ \text{k}\Omega$ was chosen since it provides a gain of 26.641, which is only a 1.3% difference between the desired and actual gain.

As a precautionary measure, the instrumentation amplifier weight sensor interface was designed to suppress radio-frequency-interference (RFI) using the AD623 datasheet's recommended RFI attenuation circuit [25, p. 25]. Connections between the weight sensor and the weight sensor interface are shown in Figure 2. The weight sensor schematic is shown in Figure 3.

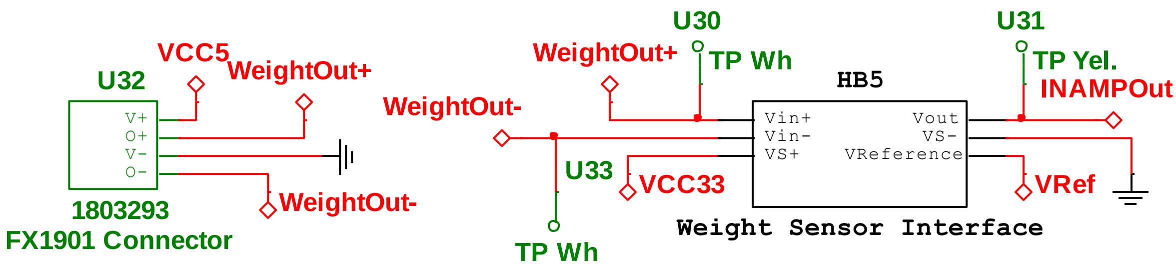

Figure 2 Weight Sensor Interface High Level Schematic

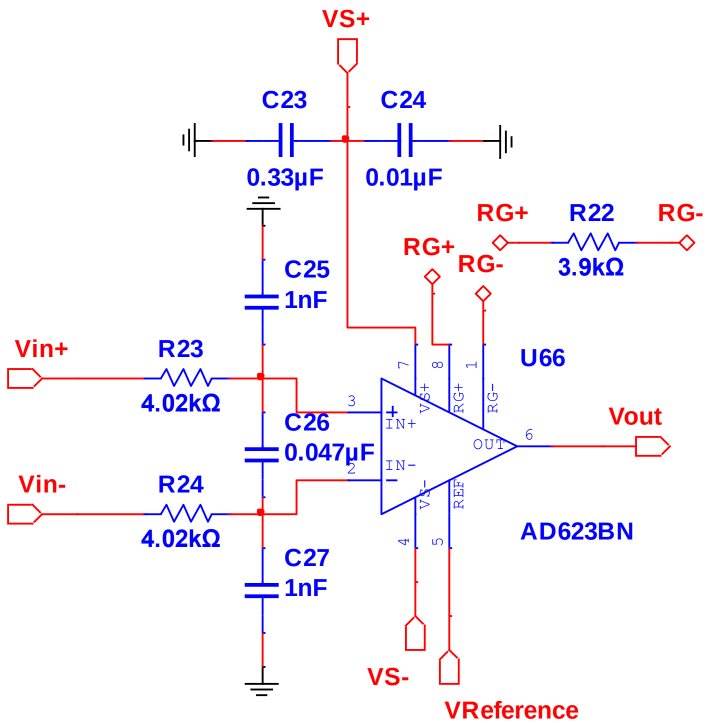

Figure 3 RFI Protected Instrumentation Amplifier Weight Sensor Interface Schematic

The board layout for the weight sensor interface is shown in Figure 4.

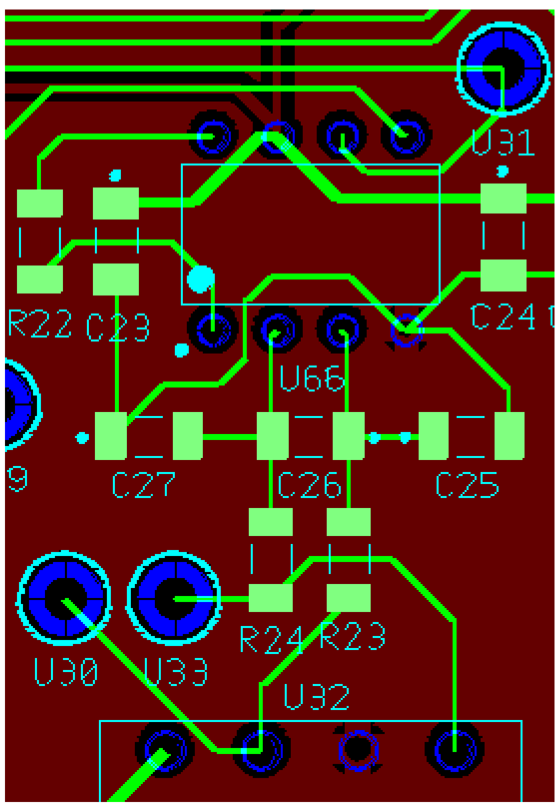

Figure 4 Weight Sensor Interface Board Layout

Due to an issue that was found while testing the weight sensor interface, a modification to the design was made. When measuring the instrumentation amplifier output voltage when connected to the load cell, the output did not change from 1.65 V when the load cell output changed. This is because the load cell's common mode voltage is 2.5 V when supplied with 5 V, which when amplified, saturates the instrumentation amplifier since its supply voltage is only 3.3 V. To ameliorate this issue, the supply voltage for the sensor was changed from 5 V to 3.3 V so that the common mode voltage was lowered to 1.65 V. This change in supply voltage does affect the mapping between applied weight and the voltage outputted by the instrumentation amplifier. Instead of outputting 3.3 V when 5 pounds of weight is applied to the load cell, the maximum voltage is now 2.739 V. Even so, the MSP430's 12-bit ADC has a high enough resolution where this change in supply voltage has very little effect on functionality.

Water Sensor Interface

The amount of water present in the water bowl is measured using two OLS500D3 liquid water level sensors [26] placed at different heights along the side wall of the bowl. The OLS500D3 is supplied with 5 V and outputs a high 4 V DC output when in contact with air, and a low 0 V DC output when in contact with water [26]. Each sensor's output is connected to the MSP430 through identical water sensor interfaces, which reduce the 4 V output voltage to ~3 V using a voltage divider and a unity gain buffer in series, as shown in Figure 6. Reducing the sensor's output voltage is necessary to prevent damage to the MSP430 Input/Output pins. The voltage divider reduces the output voltage to about 3 V while the unity gain buffer eliminates loading effects by isolating the sensor and the MSP430 circuits. Figure 5 shows the connections between the sensors and the sensor interface.

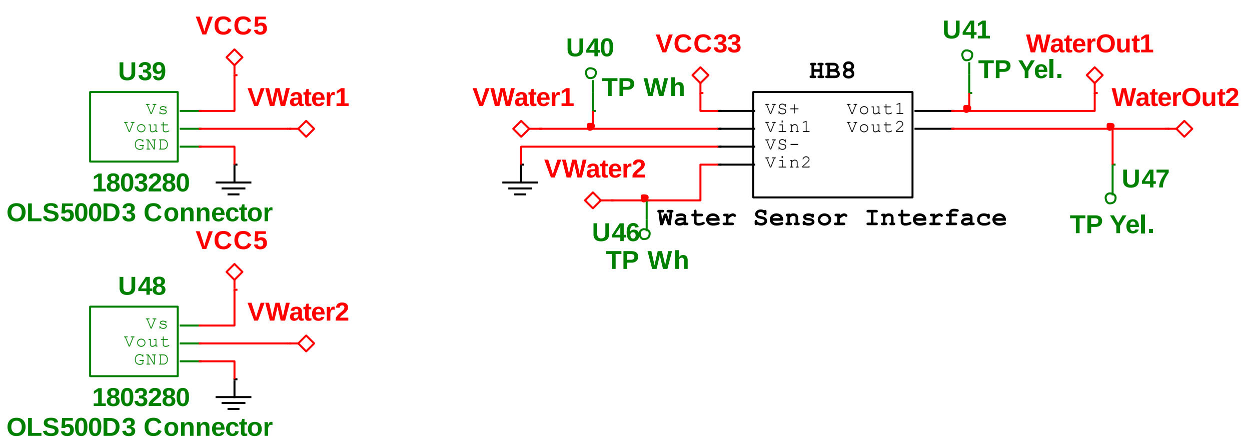

Figure 5 Water Sensor Interface High Level Schematic

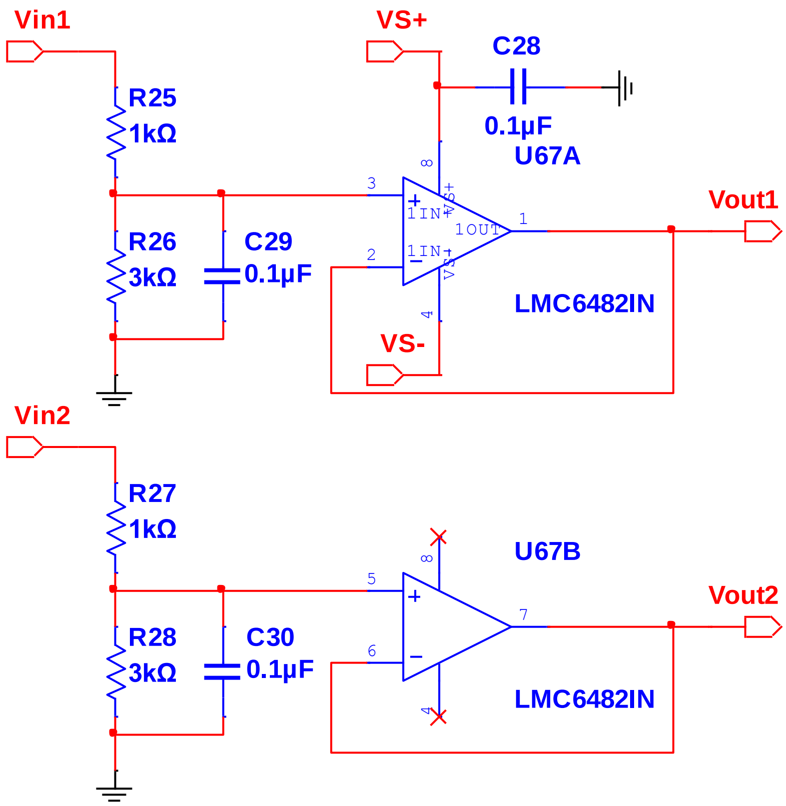

Figure 6 Water Sensor Interface Schematic

The board layout for the water sensor interfaces and the water sensor connectors is shown in Figure 7.

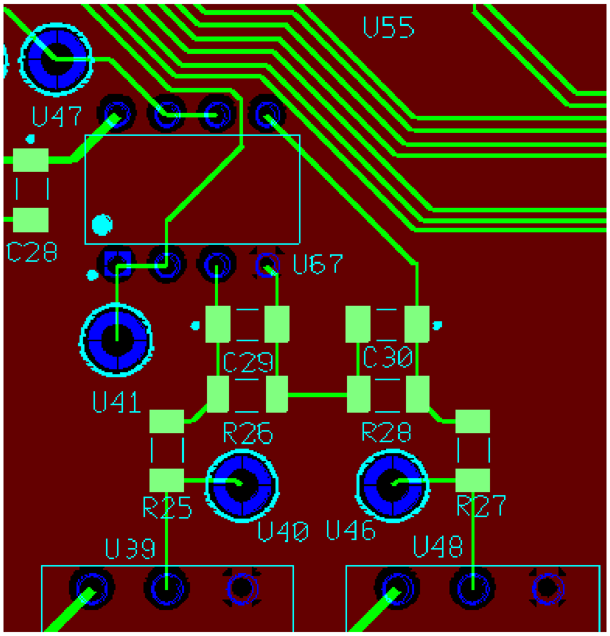

Figure 7 Water Sensor Interface Board Layout

Stepper Motor and Driver

Dry pet food is transferred from the food container to the food bowl through the excitation of a stepper motor, which rotates a disk containing 6 equally spaced and sized holes that is covered in more detail in the Dispenser Disk Structure. For this implementation, the SanMotion SF2423-10B41 bipolar stepping motor was used since the motor is relatively inexpensive, the motor shaft produces an adequate 560 millinewton meters of torque, and the motor has a high degree of precision and control since the motor has a small step angle of 1.8 degrees [27].

To simplify the excitation of the motor's two phases, the Texas Instrument DRV8434RGER motor driver was implemented [28]. This motor driver simplifies the process of controlling the stepper motor since it contains various configurations and settings that change how the stepper motor operates, and the driver only requires a single input to control the motor, assuming the proper enable pins are set. Thus, the microcontroller must only send a single pulse-width-modulated (PWM) signal to control the stepper motor. A simplified overview of the stepper motor driver's input and output connections are shown in Figure 8, from the DRV8434RGER's datasheet [28].

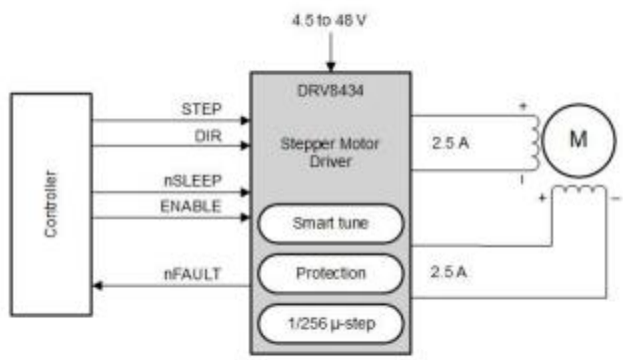

Figure 8 DRV8434 Simplified Schematic

Using the DRV8434RGER's datasheet [29], the circuit schematic shown in Figure 9 was implemented. The corresponding connections to the stepper motor are shown in Figure 10. The values for bypass capacitors C_1, C_2, C_4, C_5, C_6 and the resistor R_4 were taken from a recommended layout for the stepper motor driver from the datasheet [29, pp. 13, 33, 40]. A large capacitance of 100 microfarads was chosen for the bulk capacitor C_3 to maintain a stable input voltage during times of excessive current demands from the motor. Since the stepper motor is rated at 24 V input [27], appropriately rated capacitors were chosen (50 V in this case).

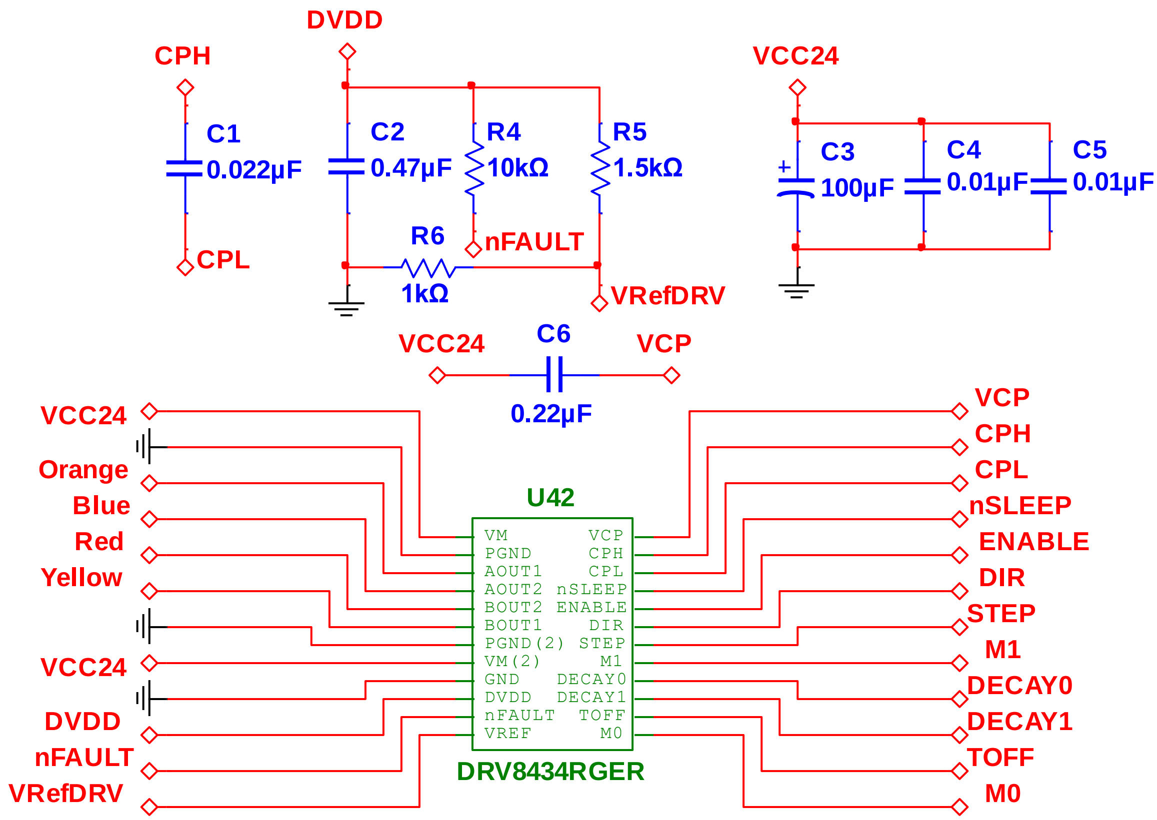

Figure 9 Stepper Motor Driver Schematic

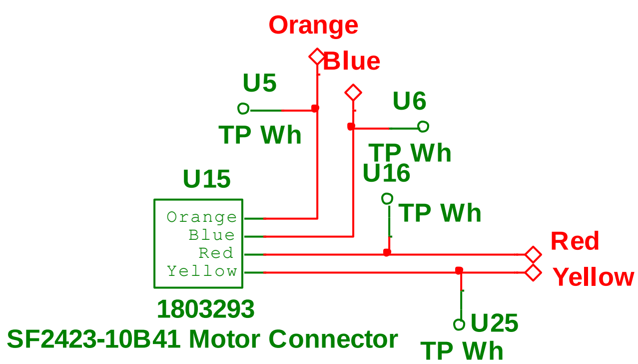

Figure 10 Stepper Motor Connections

Since the SF2423-10B41 is rated at 1 A [27], the remaining resistors R_5 and R_6 were selected to limit the full-scale current (the maximum current driven through either motor winding) provided by the motor driver to 1 A. The full-scale current is dependent on the V_{ref} pin's voltage through the provided equation [29, p. 34]:

$$I_{FS}(\mathrm{A}) = \frac{V_{REF}(\mathrm{V})}{1.32\ (\mathrm{V/A})} \Rightarrow V_{REF} = I_{FS}(\mathrm{A}) \cdot 1.32(\mathrm{V/A}) = 1(\mathrm{A}) \cdot 1.32(\mathrm{V/A}) = 1.32\ (\mathrm{V})$$

Using a voltage divider formed by resistors R_5 and R_6 connected to the digital voltage $DVDD =$ 3.3 V and ground, the voltage for V_{REF} was set to 1.32 (V). The datasheet also recommended that the parallel combination of these resistors be less than 50 kΩ [29, p. 13]. With the implemented resistor values of $R_5 = 1.5\ \text{k}\Omega$ and $R_6 = 1\ \text{k}\Omega$, the reference voltage and parallel resistance specifications are satisfied as shown below:

$$V_{REF} = V_{DVDD}\frac{R_6}{R_5 + R_6} = (3.3\ \text{V})\frac{1\ \text{k}\Omega}{1.5\ \text{k}\Omega + 1\ \text{k}\Omega} = 1.32\ \text{V}$$

$$R_{parallel} = R_5||R_6 = \left[\frac{1}{R_5} + \frac{1}{R_6}\right]^{-1} = \left[\frac{1}{1.5\ \text{k}\Omega} + \frac{1}{1\ \text{k}\Omega}\right]^{-1} = 600\ \Omega < 50\ \text{k}\Omega$$

The board layout for the stepper motor driver is shown in Figure 11. The 24 V supply voltage and ground connections have relatively thick traces to handle the excessive current that is supplied to the stepper motor. Through-hole capacitors were used to increase the number of connections to the bottom ground plane of the board in place of vias. Most of the traces in the top left of the board layout are connected to the MSP430 for configuring the motor driver and sending the PWM signal. Finally, the motor driver's thermal pad is connected to a copper square on the top side of the board, which contains a via connection to the ground plane. This method of cooling the motor driver is adequate as has been shown during the stepper motor testing phase.

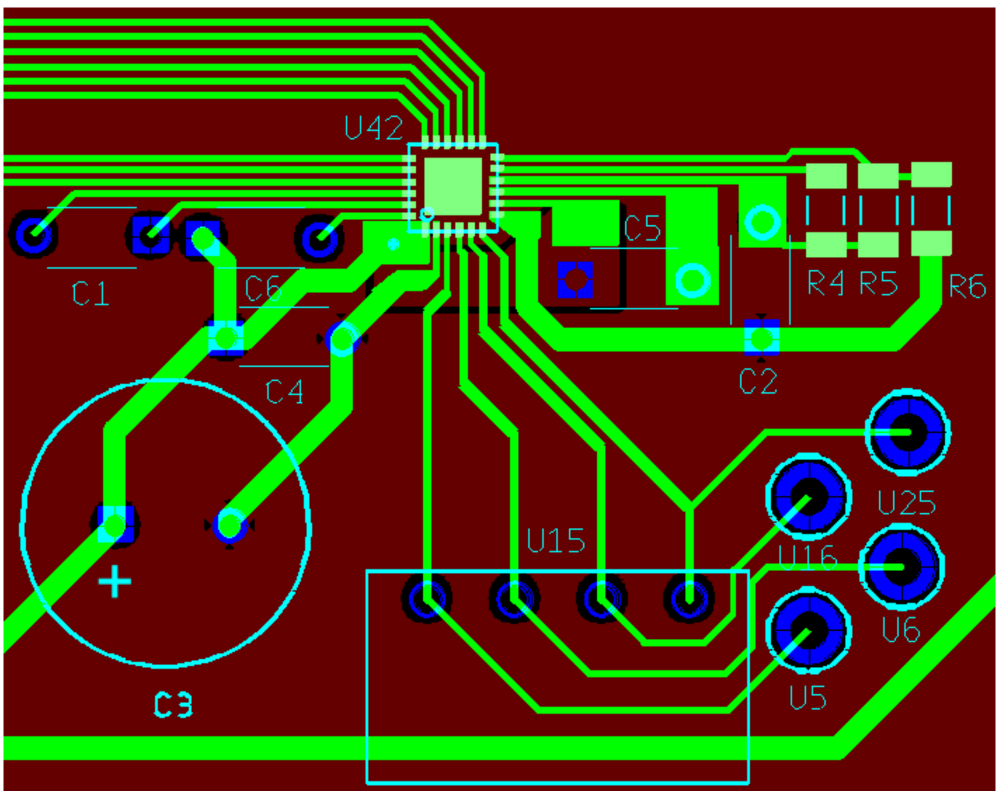

Figure 11 Stepper Motor Driver Board Layout

Peristaltic Pumps

The Smart Pet Feeding Station dispenses water from the water tank into the appropriate bowl using two 1150 Adafruit peristaltic pumps, rated at 12 V, 300 mA [30]. The circuitry implemented for the peristaltic pumps is shown in Figure 12. Each pump receives 12 V from the 12 V voltage regulator, labeled “VCC12” in the figure. The pumps are operated using a signal from the MCU labeled “PumpEnable”. Specifically, this signal operates a transistor switch that when powered with a high signal from the MCU, allows the pump to draw current. The transistor used for this part of the project is the KSP2222ABU BJT from Onsemi [31]. Both pumps are enabled by the same signal from the same port pin on the MCU, therefore they will always run in tandem. Notably, VCC12 initially experienced significant overheating whenever the pumps ran for more than 30 seconds or so. As a result, heat sinks were applied to VCC12 in order to allow for consistent use of the peristaltic pumps as needed, and to avoid damage to the 12 V voltage regulator itself.

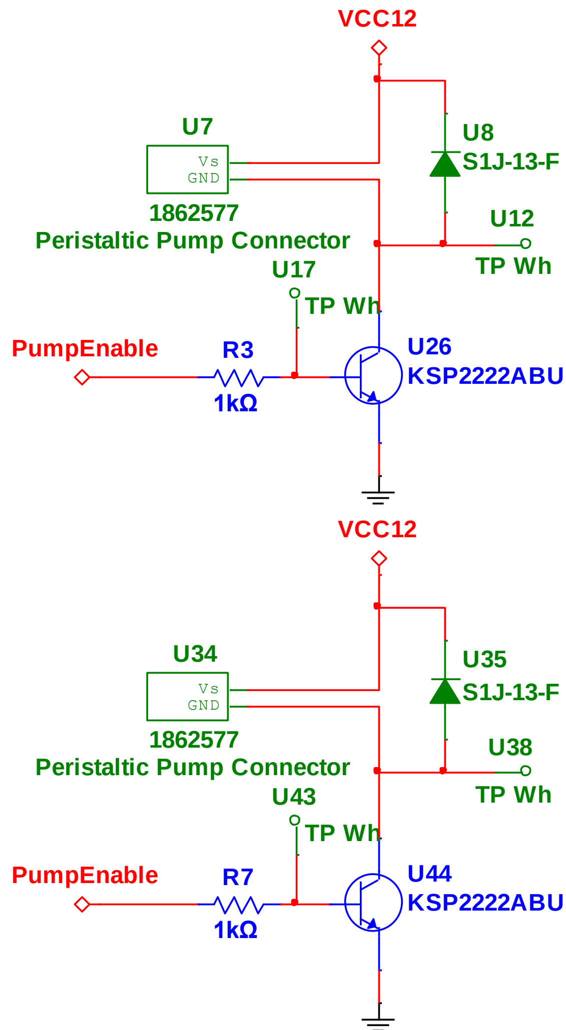

Figure 12 Peristaltic Pump Schematic

The board layout of the peristaltic pump switches is shown in Figure 13.

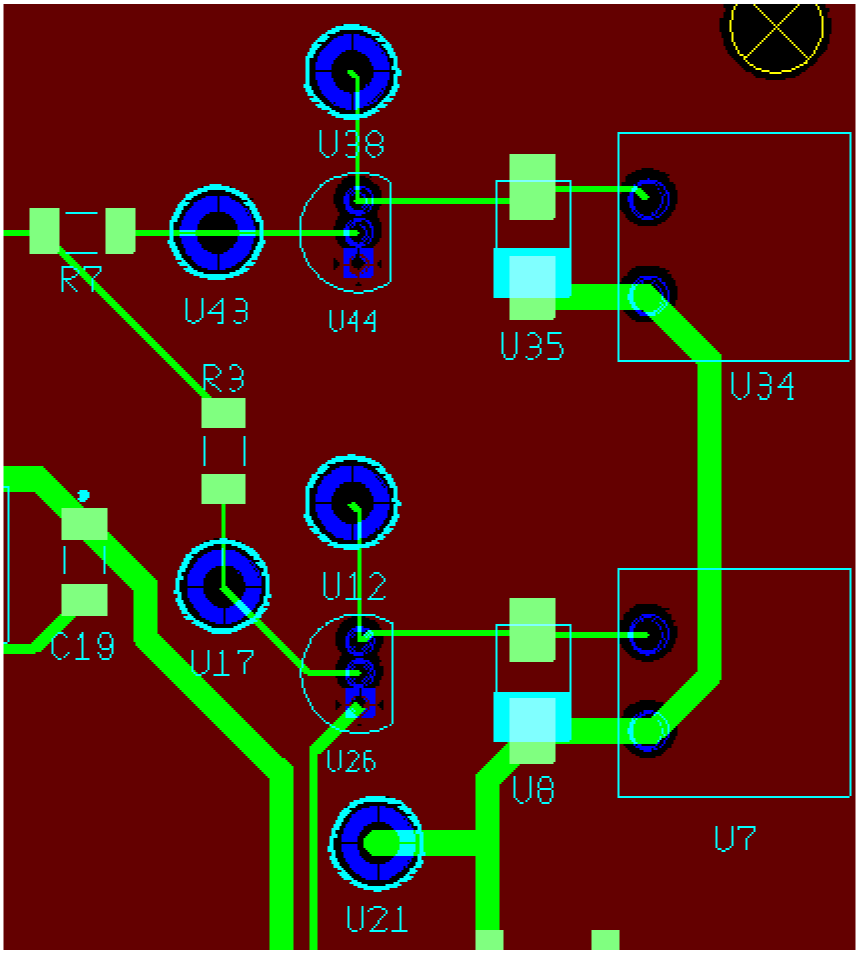

Figure 13 Peristaltic Pump Switches Board Layout

Buttons

A set of six buttons is incorporated within the Smart Pet Feeding Station to allow users to interact with the system. Figure 14 shows the six identical button circuits as hierarchical block diagrams in the main circuit. Entering one of these blocks yields the circuit in Figure 15. This interface works as a safe connector circuit to a sensitive microcontroller pin. If the switch is open, then the microcontroller pin is tied to VCC = 3.3 V through an RC low pass filter with τ =16.8 μs and fc ≈ 60 kHz. If the switch is closed, then the microcontroller pin is tied to ground through an RC low pass filter with τ =10 μs and fc = 100 kHz. These low pass filters are present to block any radio signal interference caused by metal wires on or near buttons accidentally acting as small antennas. According to the datasheet for the D6C SPST push button used in this project, the maximum rated current is 10 mA [32]. The value of R8 is determined by limiting the current to be less than 5 mA when the switch is closed. The resistance R8, with this condition, is given by

$$R_8 > \frac{V_{CC} - V_{GND}}{5\text{ mA}} = \frac{3.3\text{ V}}{5\text{ mA}} = 660\ \Omega$$

The uClamp3301H TVS Diode [33] is a special diode-like device which protects the sensitive microcontroller pin from any electrostatic discharge that might occur.

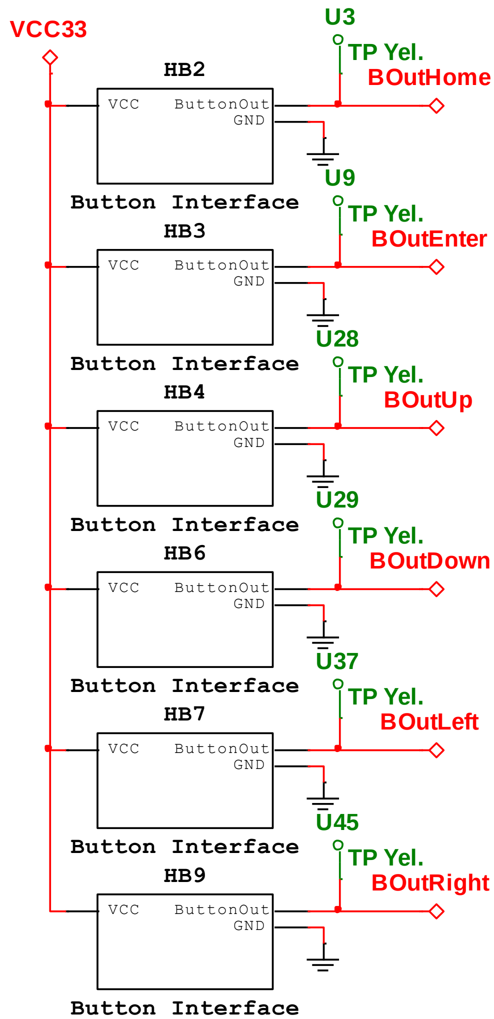

Figure 14 Button Interface Hierarchical Blocks

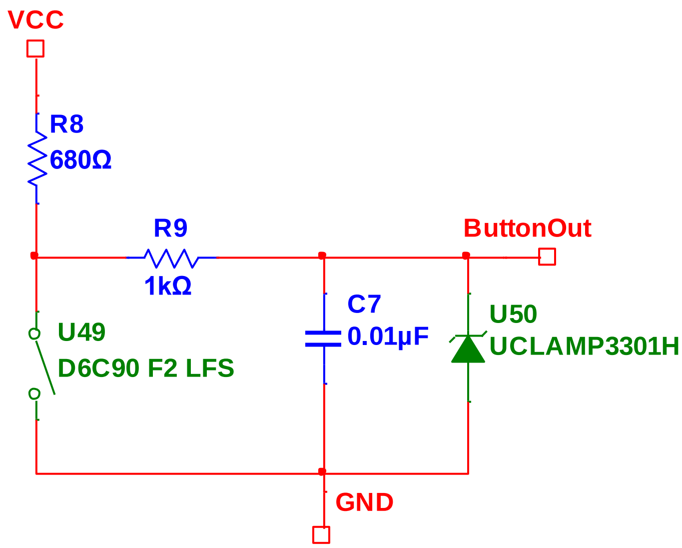

Figure 15 Button Interface Schematic

The board layout for the pushbuttons and the button interfaces are shown in Figure 16.

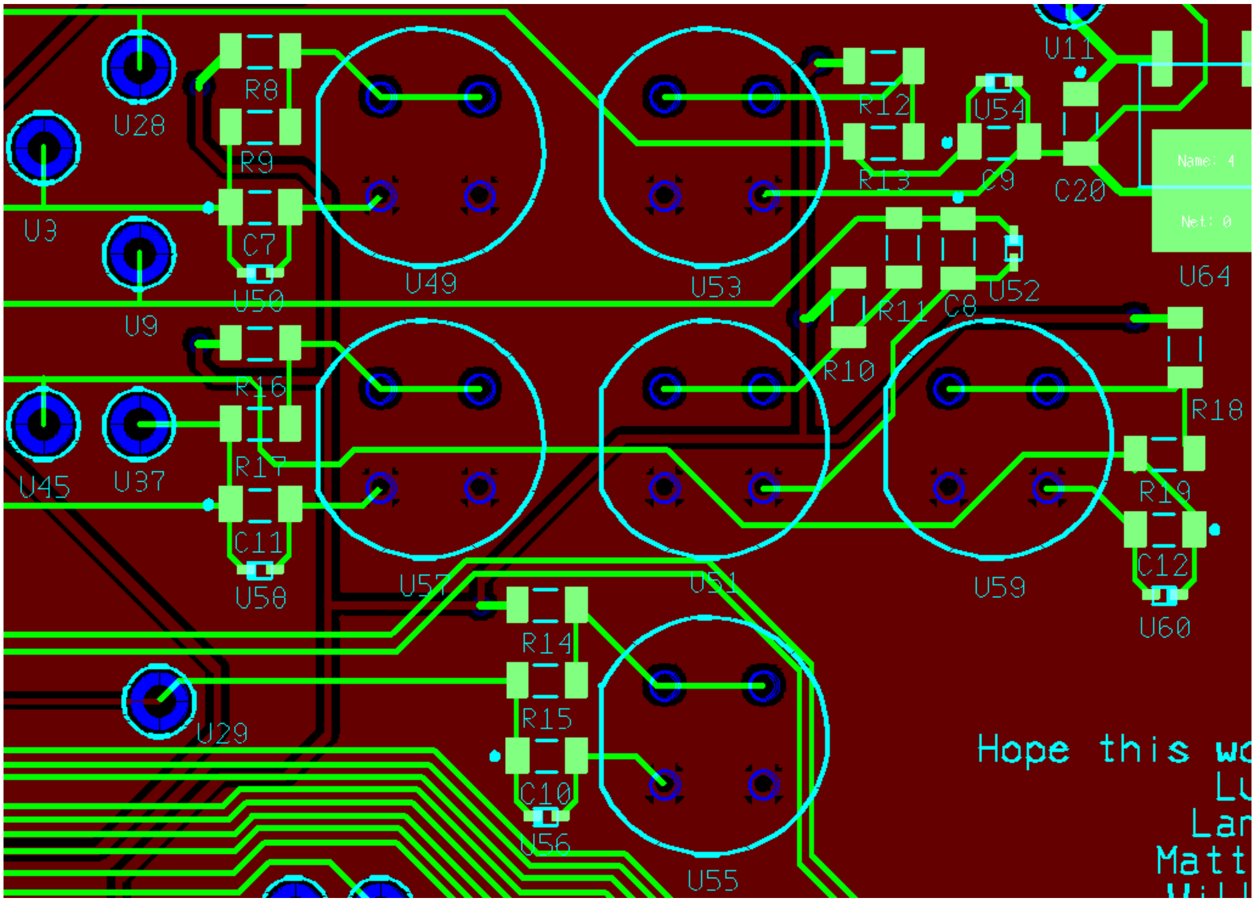

Figure 16 Push Buttons Board Layout

LCD Screen

An LCD screen is incorporated in the design of the Smart Pet Feeder to show the user important information and allow the user to interact with the system. For this implementation, the ACM2004F 20x4 LCD display from AZ Displays [34] was used. The LCD screen interface is shown in Figure 17. This figure shows the digital logic supply V_{dd}, the contrast voltage V_o, the register select bit, read/write select bit, eight data bits, and the backlight 6 V supply voltage. The voltage divider shown on the right side of the figure establishes the contrast voltage. In this example, it would be expected that the contrast voltage is approximately 1 V. However, during LCD testing, it was found that the contrast voltage was about 2.2 V, meaning that the voltage divider output and the LCD's contrast voltage pins are not independent from each other. If a unity gain buffer were placed between the two sections, this loading effect may not be present. To counteract this issue, a 100 kΩ potentiometer [35] was used to replace resistors R_1 and R_2 so that the contrast voltage could be readily changed to any voltage between 0 V and 5 V.

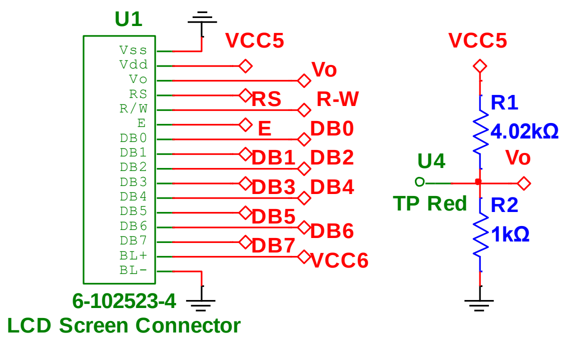

Figure 17 LCD Interface Schematic

The board layout for the LCD interface and connector are shown in Figure 18.

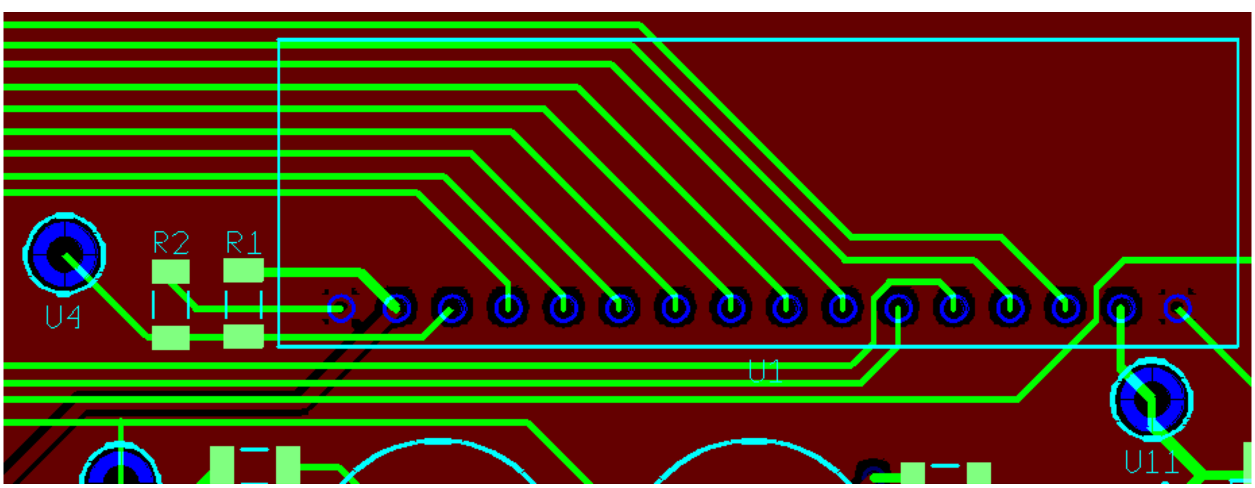

Figure 18 LCD Interface Board Layout

Power Supply

To allow each of the system components to operate correctly, proper power supplies were selected to deliver the necessary voltages and currents. System power is provided from a GlobTek 24 V, 65 W AC/DC adapter [36], from which lower voltages are derived using various voltage regulators. Power is delivered at a voltage of 24 V to supply the stepper motor, which is rated at 24 V, 1 A. For low current system components, including the MSP430 microcontroller, motor-driver, pushbuttons, operational amplifiers, instrumentation amplifier, and the load cell, 3.3 V were required, thus the LT1121CZ-3.3 (3.3 V, 150 mA) voltage regulator from Analog Devices [37] was selected to supply power to these components. Another group of low current devices that was used include the water level sensors and LCD digital logic, which both required 5 V, thus the LT1121CZ-5 (5 V, 150 mA) voltage regulator from Analog Devices [38] was selected to supply power to these components. The next power supply that was implemented was the Texas Instruments UA78M06CKVURG3 (6 V, 500 mA) voltage regulator [39], which was originally used to power the LCD's backlight (drawing 340 mA). During testing, the voltage from this regulator was shown to drop rapidly after starting the system due to overheating. Ultimately, the decision was made to not use the 6 V regulator since the LCD was still usable without it. The next voltage regulator that was used is the Onsemi MC7812CDTRKG (12 V, 1 A) [40] voltage regulator, which was used to power the two peristaltic pumps. This regulator had the same issue as the 6 V regulator, however the application of heatsinks quickly resolved the overheating issue. The power supply system for the Smart Pet Feeding System is shown in Figure 19. The bypass capacitors used for each regulator were recommended in the corresponding regulator datasheets.

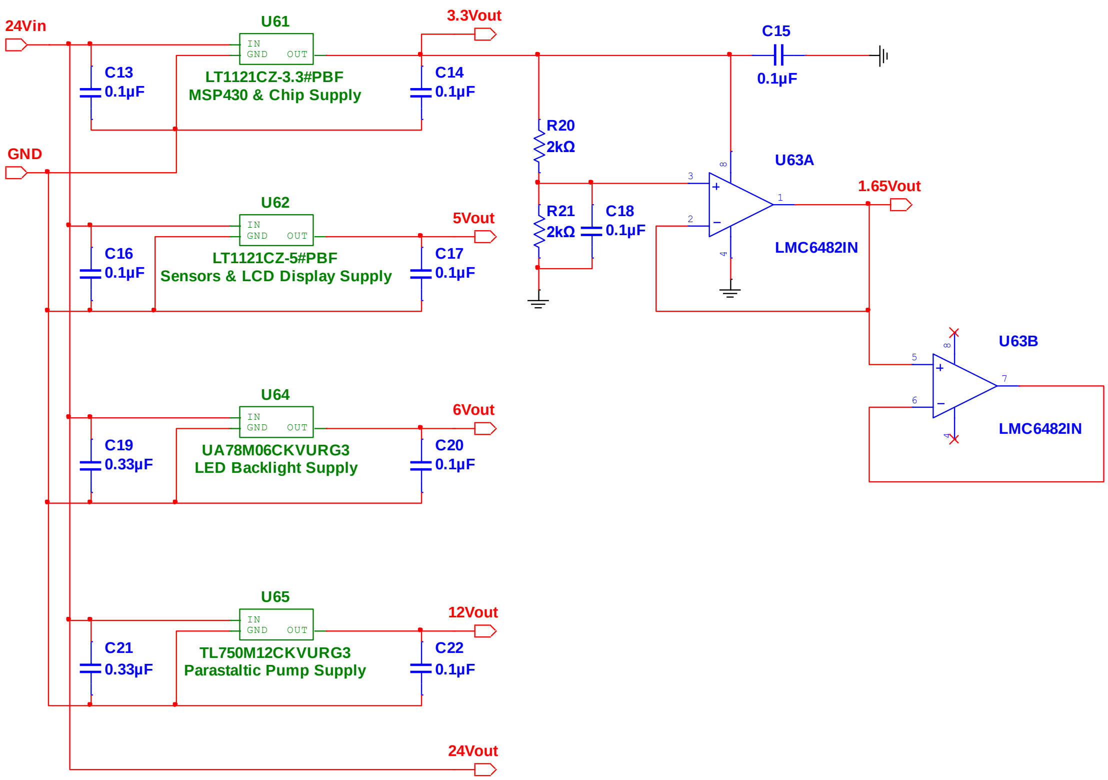

Figure 19 Power Supply Schematic

The amount of power needed to supply the system was determined by considering the power delivered and power used by voltage regulators and other system components. A conservative approach to determining the system power is to assume that each voltage regulator is outputting the maximum rated current. If it is assumed that each of the mentioned voltage regulators is performing at the maximum current, the power use of the system is

$$\begin{aligned} P_{sys} &= P_{step} + P_{3.3\,V} + P_{5\,V} + P_{6\,V} + P_{12\,V} \\ &= 24\text{ V} \cdot 1\text{ A} + 24\text{ V} \cdot 150\text{ mA} + 24\text{ V} \cdot 150\text{ mA} + 24\text{ V} \cdot 500\text{ mA} + 24\text{ V} \cdot 1\text{ A} \\ &= 67.2\text{ W} \end{aligned}$$

Since the peristaltic pumps are limited to 300 mA each, this implies that the 12 V regulator is outputting a maximum of 600 mA, meaning that the maximum system power is

$$P_{sys}^{*} = P_{sys} - 24\text{ V} \cdot 400\text{ mA} = 57.6\text{ W}$$

Thus, the chosen 24 V, 65 W supply is adequate for powering the system.

Software

Software was written for the MSP430FR2355 microcontroller using Code Composer Studio [17]. The first step in creating the software in the device was setting up all of the relevant port pints for each of the components so that the MSP430 could send and receive signals from these components. The connections that are made between the MSP430 and the different components are shown in Figure 29 in the Appendix. Once port pin connections were defined, the base program was created. Since the program relies on time to determine when a water or food dispense event must occur, the MSP430's Real-Time-Clock (RTC) counter [7, p. 415] is used to increment a global counter variable every second. This counter keeps track of the current time of day so that dispensing events can be executed and updated while active.

Task Scheduler

An important functionality of the device is collecting information on different inputs, including push button input, water sensor input, and weight sensor input. In order to make the collection of the information related to these components controllable, a task scheduler was implemented, which stores an array of function addresses, and the corresponding execution period for each of the functions. The rate of execution of each function is therefore dependent on the rate at which the task scheduler is executed and the specified function execution period. The task scheduler is controlled by the MSP430FR2355's Timer_B0 [7, p. 391], and executes at a rate of 10 kHz. The task scheduler contains three functions for updating water sensor state variables (updated at a rate of 4 Hz), weight sensor state variables (updated at a rate of 1 kHz), and push button state variables (updated at a rate of 1 kHz).

Sensor and Button Data Structures

Important information for each of the system components are stored in appropriately defined data structures. The most notable data structures are for the weight sensor, water sensor, and push buttons. The definitions for these data structures are shown in the Appendix in Figure

34. The weight sensor data structure contains a size 1024 circular buffer, which stores the 12-bit Analog-to-Digital values outputted by the MSP430's ADC.

The average weight value in the buffer is found by adding all 1024 values and performing a 10-bit right shift to the cumulative sum. This averaging filter smooths out the input signal and eliminates impulses, however there is some delay since averaging filters lag behind the original signal. The water sensor and pushbuttons types have similar definitions since they both store images of the input ports. The different variables are used in place of an explicit finite state machine.

Dispense Events

To keep track of each event, the time it occurs, the amount of substance to be dispensed, and which events have been completed, dispense event data structures were created as shown in Figure 35 in the Appendix. A data structure was also created for maintaining the water level within the bowl. Within the main program file, an array of pointers to dispense events is defined. When a user creates a new event, the feeding or watering event address is stored in this array. The events within the array are constantly checked to see if the current time is equal to the event time and are executed accordingly.

Physical Structure

The physical structure of the device was primarily constructed out of wood and contained a couple of 3D printed parts. The device's physical structure is shown in Figure 36 in the Appendix.

Roberval Balance

Beneath the food bowl and above the weight sensor is a part called a "Roberval Balance". This part was designed in Solidworks, and 3D printed. Essentially, the only purpose of this part was to keep the weight of the bowl, and whatever food inside it, centered on the weight sensor while also maintaining lateral stability. The part is composed of 6 pieces: a base, a platform for the bowl, and 4 connecting "arm" pieces. A Roberval Balance works by taking advantage of the parallel stabilities of a parallelogram such that it allows smooth movement along a vertical axis, while disallowing any movement along lateral axes. The part used in this project differs from a conventional Roberval Balance by being single sided and featuring a space for the weight sensor directly beneath the center of the platform portion of the part. Below are screenshots of the part in Solidworks displayed from an angled, side, front, and top view to best illustrate how it was put together and functions.

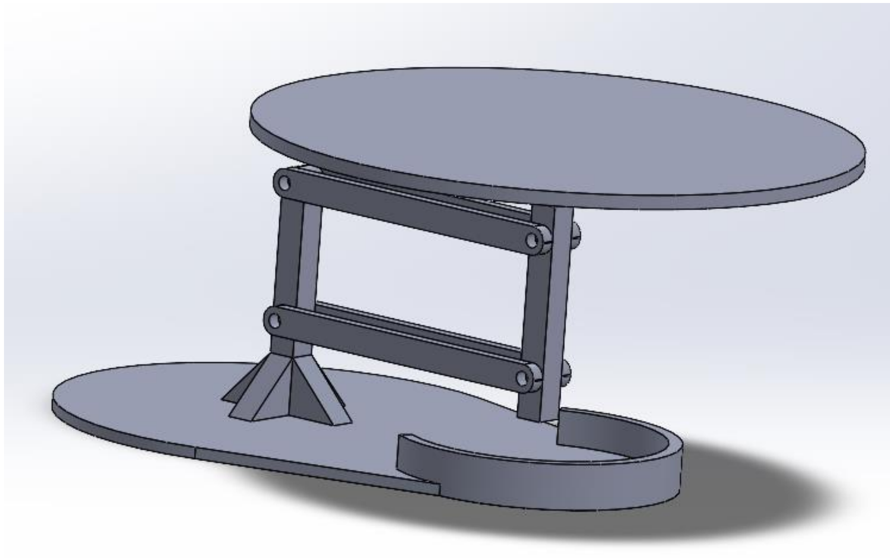

Figure 20 Roberval Balance, Angled View

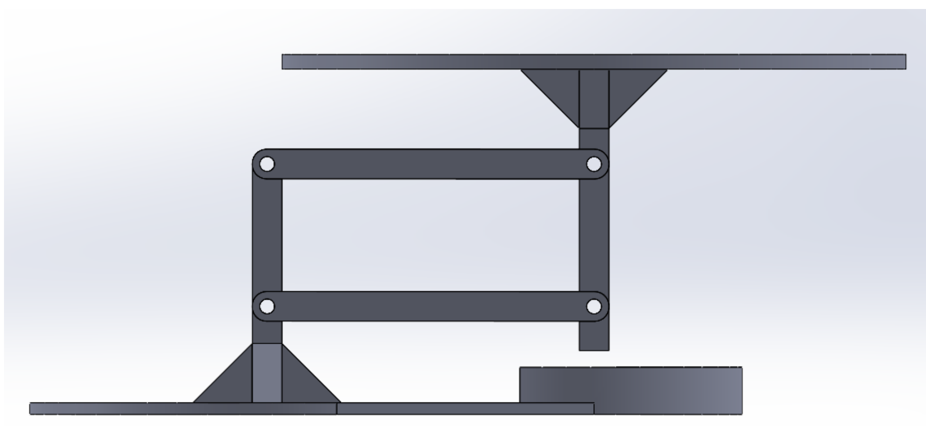

Figure 21 Roberval Balance, Side View

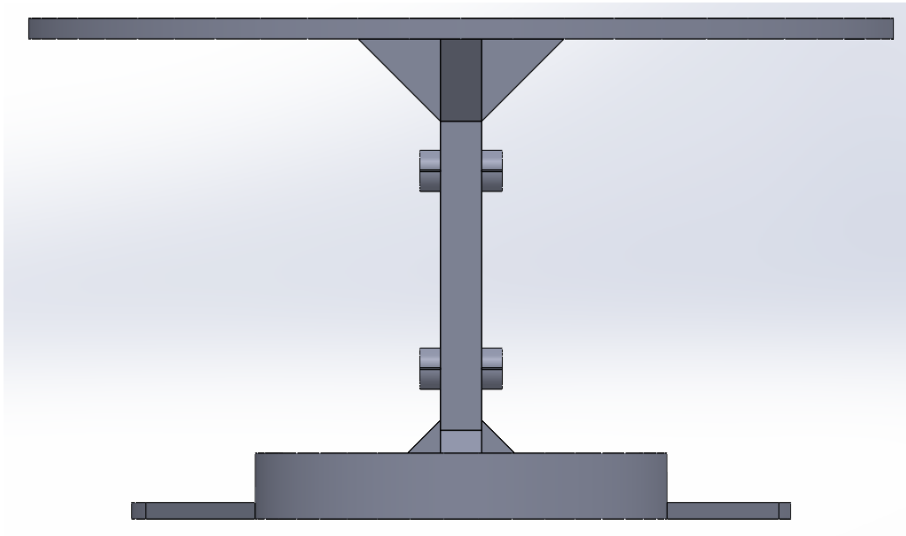

Figure 22 Roberval Balance, Front View

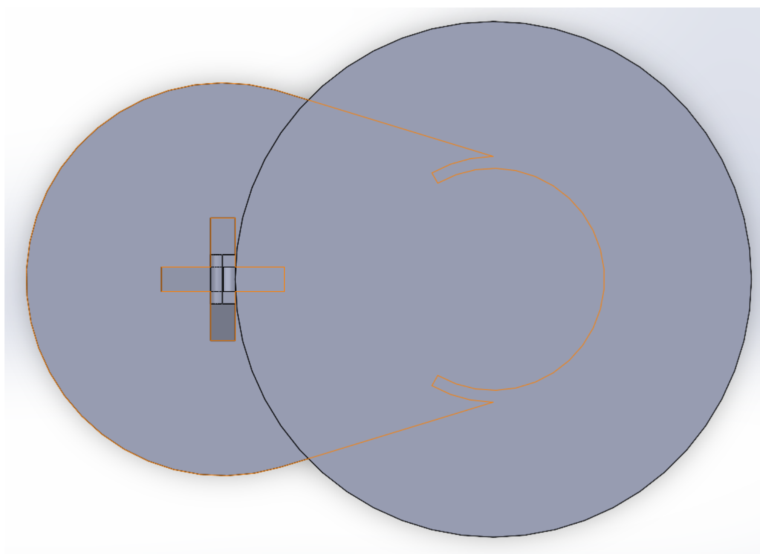

Figure 23 Roberval Balance, Top View

Dispenser Disk Structure

A circular disk was designed to be mounted onto the rotor of the food dispenser stepper motor and is shown in Figure 24, Figure 25, and Figure 26. The disk contains 6 evenly spaced holes that are each 15 mm in diameter. The disk sits under a small food chute opening about the size of the hole, and when one of the holes is lined up with the chute, food can pass through the disk, but when the chute opening is lined up with the space between the holes, food is unable to pass. Thus, when the disk is rotated using the stepper motor, food is dispensed at a controlled average rate.

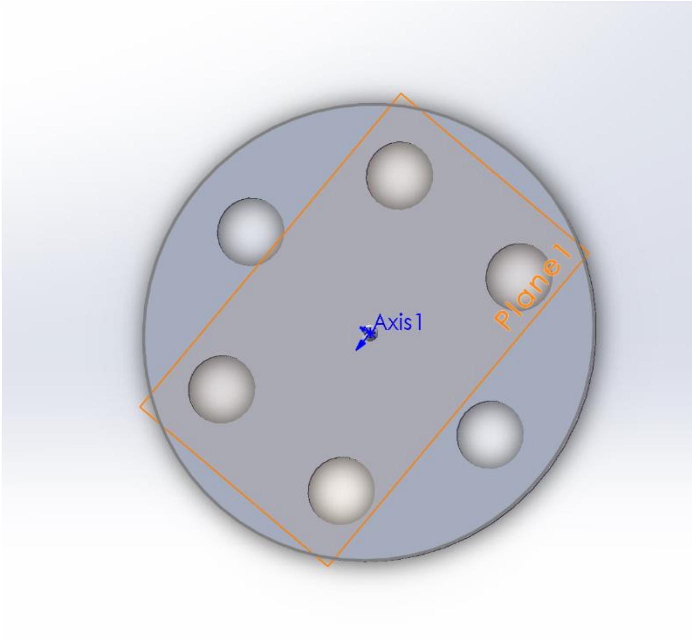

Figure 24 Dispenser Disk Top View

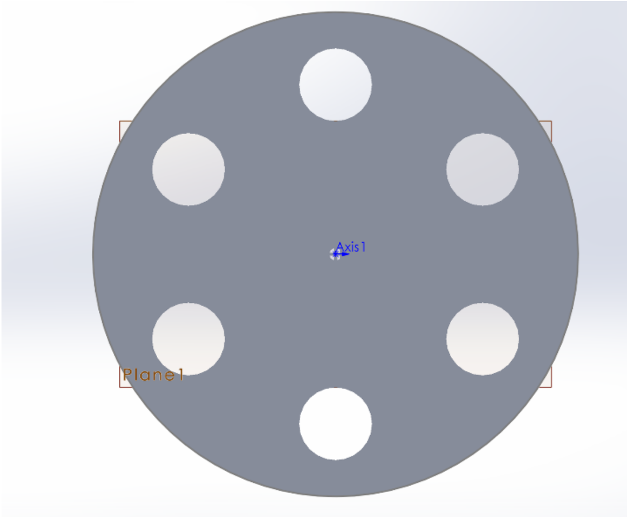

Figure 25 Dispenser Disk Bottom View

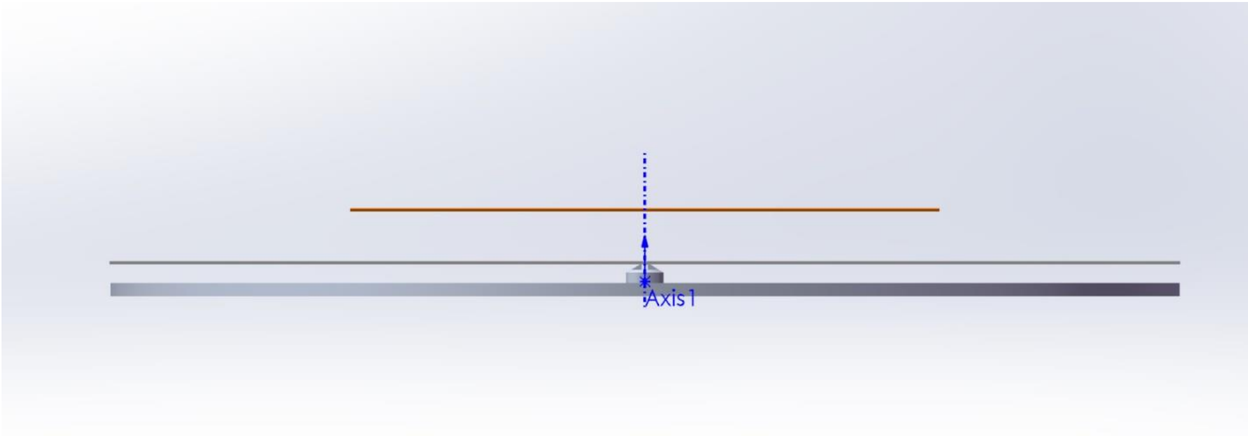

Figure 26 Dispenser Disk Side View

Wood Frame

The wood frame was constructed using a single piece of plywood. The side L shapes were 36”x16” with a 32”x8” rectangle removed, so that they can fit together into a 40”x16” rectangle. The top lid piece and the piece that holds the food and water bowls are each 18” long and almost 8” wide. The large base is a 16”x18” rectangle. The rest of the plywood pieces were cut to be 16 ½” long to fit between the two L shapes. These were 4” wide for the front panel on the bottom, 8” wide for the back panel, and around 4” wide for the front panel on the top layer. In addition to this, we added 3 panels cut from a ¾”x6” pine board. One for the shelf that holds the motor, one for the screen holder just beneath the front panel at the top, and one for the PCB board holder just beneath the screen.

Project Time Line

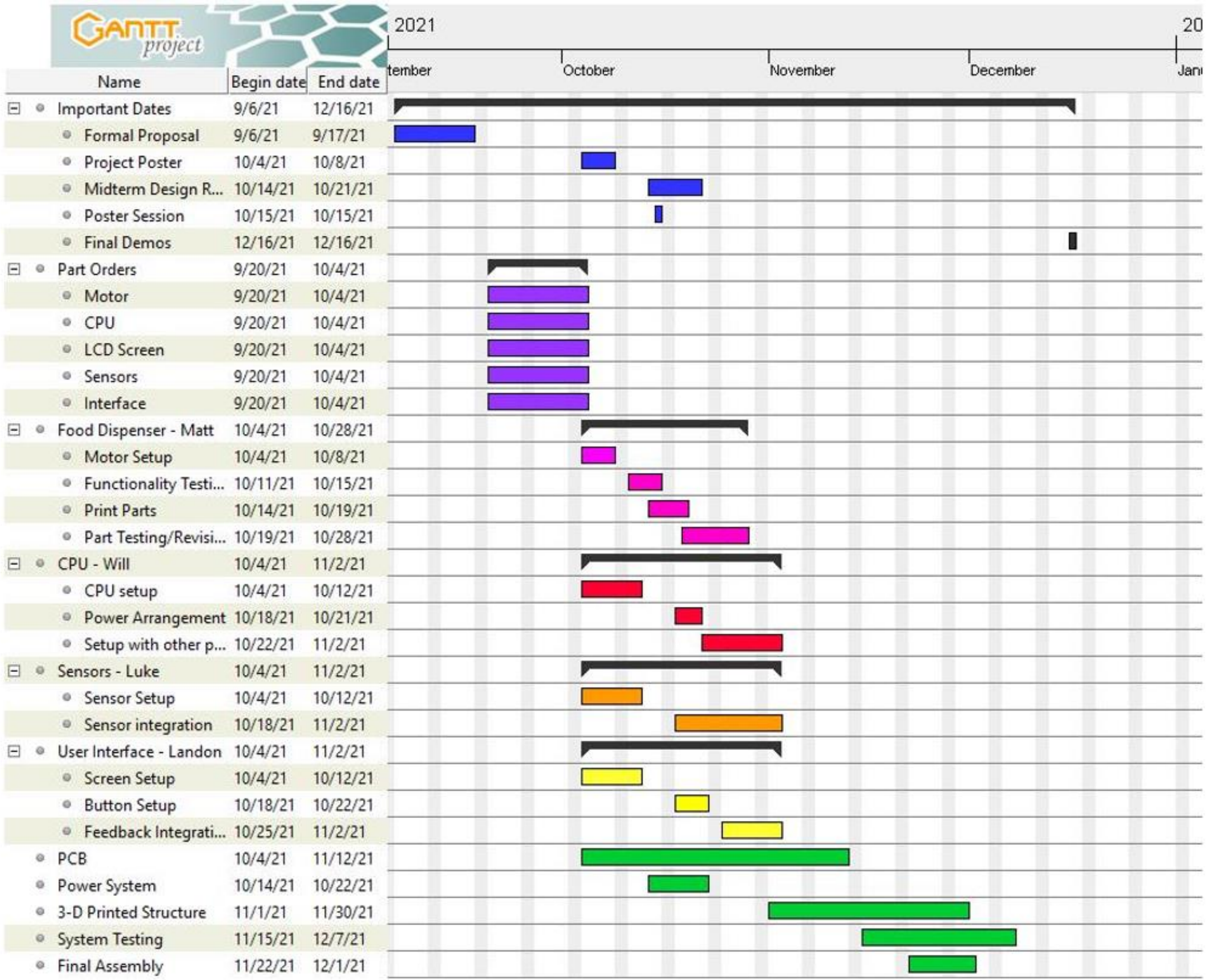

Figure 27 Original Gantt Chart Schedule

The above Gantt chart shows the original timeline of the slated project deadlines, original deadlines of each section of the project assigned specifically to each team member, and timelines that were otherwise relevant to the project. All sections of the timeline were color coded to indicate that they were related in their content, and sections that represented tasks to be completed were assigned to whichever team member was expected to complete that section's deliverable. The first section of the project is the "important dates" section that includes all the most relevant and important deadlines for the capstone project. The "part orders" section lays out an estimated waiting time of about two weeks between ordering and receiving the parts necessary to continue the project. The main sections of the project that were specifically divided between the team members include the food dispenser, the CPU, the sensors, and the user interface. Each of these sections was further divided into more manageable parts. These sections of the project were expected to be done in parallel as they were largely unrelated to each other and were all required to be completed before the final sections of the project. Lastly, the final sections of the timeline are all colored green, not because they are particularly related in content, but rather because they were the final parts of the project and required collaboration between all team members. These final sections were largely expected to be done in parallel as parts were redesigned and reprinted in response to testing done on the final assembly of the project.

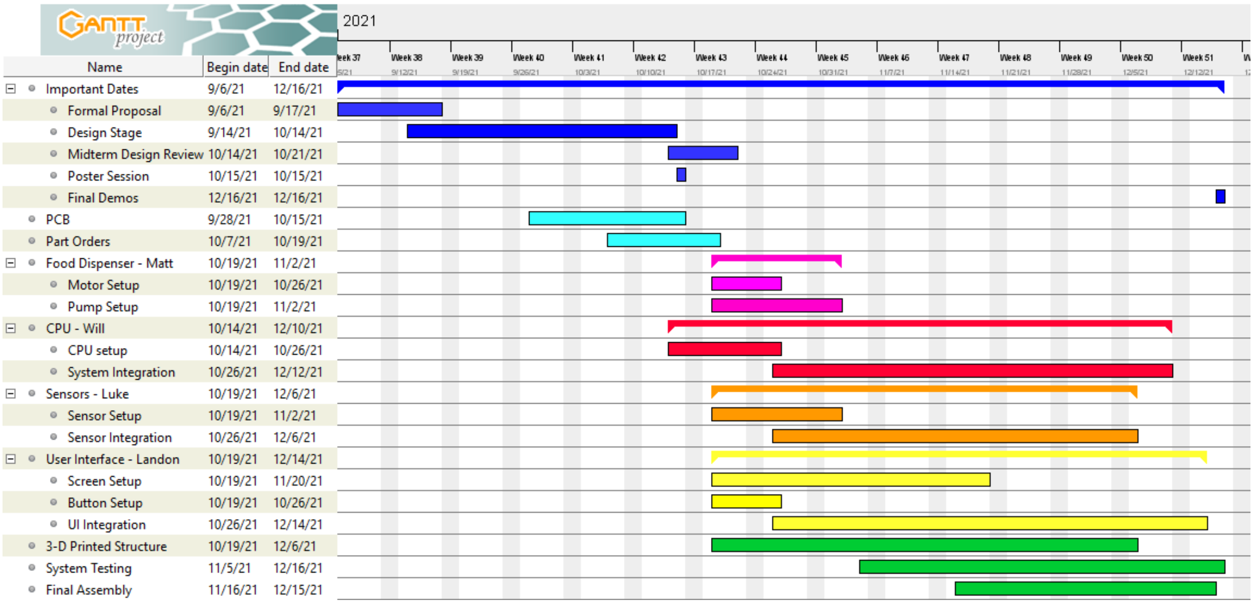

Figure 28 Final Gantt Chart Schedule

The above Gantt chart is essentially the same as the proposal Gantt chart described in the previous paragraph. Major differences include being modified for better readability, removing nonessential timelines, and extending timelines to truly reflect how the group spent time throughout the semester. The timelines were extended throughout the semester either due to issues with parts, or simply because the sections required significantly more time to complete than was anticipated. The major issues with parts include the following: parts being delivered later than expected, voltage regulators overheating, having to reconfigure the voltage divider for the LCD, and frying the original LCD. Originally, we planned to be done with the project in its entirety by the end of classes on December 6th, but in actuality, we ended up working on the project all the way up until demo day on December 16th.

Each team member has a set of primary and secondary tasks that they completed during the development and construction of the system. As his primary task, Luke was responsible for integrating the compression load cell and liquid sensors into the system. He also programmed the microcontroller to interface and collect data from the sensors. As a secondary task, Luke created the PCB board layout. Landon's primary responsibility was to create the device's User Interface by interfacing the LCD screen and the buttons to the MSP430, and programming the UI software. Landon also built most of the 3D structure. Matthew was responsible for designing the device's dispenser mechanisms and integrating them into the system. A secondary task that Matt took on was the design of the Roberval balance. William's primary responsibility was to design the physical apparatus used to dispense the food, and to construct the structure of the device. While the development of these subsystems was initially done independently, team members worked together on connecting related subsystems after the subsystems' main code and testing was completed. To ensure that independent programming was done efficiently and smoothly, proper embedded programming standards from the Barr Standard were used to ensure that code was modular, easy to understand, and loosely coupled, which facilitated easier integration of the different subsystems into the main system. Lastly, the design and construction of the device's structure and determining how all the subsystems fit together within it was largely a collaborative effort between all group members to ensure that no one subsystem was overlooked.

Test Plan

The Smart Pet Feeding Station and all of the relevant subsystems were tested using a set of test procedures that focused on the hardware, software, physical structure, and the entire integrated system. To aid in the testing process, the PCB was designed to have test points for each of the subsystems and components that allow node voltages and signals to be measured using an oscilloscope, like the National Instruments Virtual Bench [16]. The board was also designed with headers that allow the Launchpad to be removed from the PCB, which aided greatly in debugging and testing additional PCB connections.

Hardware

The first part of the system that was tested was the hardware. After the PCB was fabricated and populated with the necessary components, testing began with measuring the output voltages of the different power supplies. Since the voltage regulators receive a 24 V input voltage, the external 24 V power supply was measured to verify that the board was receiving power. After testing the external supply, the output voltages of the 3.3 V, 5 V, 6 V, and 12 V voltage regulators were measured using each regulator's respective test point. During this stage of the testing process, the 6 V and 12 V supplies were not connected to any load. After the supply voltages were tested, the next step was verifying the board connections to each of the major system components, including the buttons, LCD display, stepper motor, pumps, water sensors, and weight sensors.

The first major component that was tested was the six push buttons. The output voltage of each button was tested using the appropriate test points to verify that buttons were connected to the 3.3 V supply and that button actuation resulted in a change in the output signal.

The second component that was tested was the LCD display. When testing the digital and backlight supply voltages for the LCD, it was found that the expected 6 V backlight supply voltage input was reduced to about 4.5 V, which was insufficient for powering the backlight. Using the AstroAI Digital Multimeter [41] and its temperature probe, it was determined that the 6 V voltage regulator was overheating and that built in heat protection was limiting the supply voltage. To ameliorate the issue, heat sinks were purchased [42] and applied to the voltage regulator's package. While the heatsinks did lower the rate at which the package's temperature increased, the issue was not eliminated. Since the LCD display is still usable without the backlight, a decision was made to isolate the LCD and the 6 V voltage regulator.

Another issue that was found during testing of the LCD was the use of an inadequate contrast voltage input. In the original design of the LCD schematic, a voltage divider was established to set the contrast voltage to 1 V, however this voltage was determined to be too large after further testing was performed using the NI Virtual Bench to supply different contrast voltages. Ultimately, a 100 kΩ potentiometer [35] was used in place of the voltage divider resistors to allow the user of the system to adjust the LCD contrast.

Following the LCD hardware tests, the peristaltic pumps were tested by applying a 3.3 V input signal to the switch transistor base and measuring the voltage across the pump terminals. Although the pumps operated as expected when the input signal was applied, the pumps turned off after only 30 seconds of running, at which point a voltage of 0 V was measured across the pump terminals. Measuring the 12 V voltage regulator output, it was discovered that the device was overheating similar to the 6 V voltage regulator. Using the same heatsinks as were originally applied to the 6 V regulator, the overheating issue was solved and the pumps were able to operate with little loss in supply voltage, even though the 12 V voltage regulator operated with an equilibrium temperature of about 200 degrees Fahrenheit.

The stepper motor and motor driver were the next components to be tested. This test required that software be implemented to control and send a PWM signal to the stepper motor driver. With the stepper motor disconnected, the motor driver phase outputs were measured to verify that all necessary connections were made between the launchpad, PCB, and motor driver, and to verify that the motor would receive a proper excitation signal when connected. The motor operated as expected when it was connected to the PCB.

The next components that were tested were the weight sensor and weight sensor interface. Test points located at the sensor outputs were measured to verify the functionality of the weight sensor. Applying pressure to the weight sensor caused the voltage differential between the two outputs to increase, as expected. The instrumentation amplifier reference voltage was then tested to verify the expected value of 1.65 V. The instrumentation amplifier output was then tested. Upon measuring this output for different amounts of pressure applied to the weight sensor, it was found that the instrumentation amplifier's output voltage did not change from the reference voltage of 1.65 V. From the AD623's datasheet [25, p. 28], it was determined that the 2.5 V common mode voltage between the two instrumentation amplifier inputs lead to the saturation of the in-amp, thus the supply voltage for the weight sensor was lowered from 5 V to 3.3 volts to lower the common mode voltage from 2.5 V to 1.65 V. This change resulted in the desired operation of the instrumentation amplifier as a differential voltage amplifier.

The final hardware components that were tested were the water sensors and the water sensor interfaces. With the sensors connected to 5 V, the output voltages of the sensors were tested when in contact with air and water. As specified in the sensors' datasheet [26], the sensor outputs a 5 V signal when in contact with air and a 0 V signal when in contact with water. This behavior was confirmed by testing the test points corresponding to the sensor's outputs. The water sensor interface design was verified by measuring the interface outputs when the water sensors were in contact with water and air. When the water sensors were in contact with air and water, the unity gain buffers had outputs of about 3.3 V and 0 V respectively, verifying the design of the water sensor interface.

Software

The software for the Smart Pet Feeding station was tested using the launchpad's debugger module and Code Composer Studio's debugging tools. To test the logic of the program, or to check the state of a variable, break points were set at different parts of the program, and the values of the relevant variables was observed using the variable and expression windows in CCS. Measurements were also made using the Virtual Bench to test the functionality of the components that were related to the device's software.

Final Results

The final results for the project were generally good. The system was able to dispense dry pet food and water during the expected feeding and watering times and was also able to maintain a constant water level when instructed by the user. During watering events, the water dispenser was able to accurately dispense the correct amount of water into the bowl depending on the user specified water level. However, the food dispenser has a few issues that make the accuracy of the food dispenser a little questionable. The device structure is adequate for demonstration purposes, however it is not very aesthetically pleasing, and the electronics need to be better isolated from the food and water in a future design. In the future, the device would be made of plastic and proper covers and enclosures would be developed for the different components. While the device does contain working push buttons and an LCD display, the software for the UI was never fully implemented, meaning that the user is not able to manually program in feeding or watering times, change the date and time of day, and view event information. Instead, events have to be hard coded into the program, or activated using a button, which was done for the demonstration of the device.

Grade Breakdown

The grade breakdown for the project is shown in Table 1. Looking first at the dispensers, both the food and water dispenser turned on and off when instructed, however the food dispenser stepper motor occasionally jammed, thus for this section, the project scores a 2.

The water bowl sensors were shown to be very reliable and accurate during testing, but the accuracy of the weight sensors is not completely known. The sensor does eventually trigger the food dispenser to stop when enough weight has been applied, however it is not known whether the actual weight matches the expected weight, thus the project scores a 2.5 in the "Bowl Sensors" section.

The 3D structure of the device is adequate for demoing the device, however it is not very aesthetically pleasing, and some electrical components could be more isolated from the food and water. Still, the water sensors are isolated from water due to a hot glue coating around the edge of the holes in the water bowl, thus protection against food and water was considered and atleast partially implemented. For the "Device 3D Structure", the project scores a 2.

The User Interface for the device was largely not implemented due to issues with getting the LCD to work and software difficulties. Since the device can be controlled with buttons and the screen atleast displays what the device is doing, the project scores a 0.5 for User Interface.

The final section to look at is the "Device Operation" section. The water dispenser subsystem of the project works very well since the correct amount of water is dispensed during watering times, and the water level in the bowl is maintained when instructed by the user. While the food dispenser portion of the project dispenses food and is able to weigh the food, the accuracy is questionable and the dispenser mechanism itself needs some work, thus the project scores a 2.5 in this section.

Points	**Dispensers**	**Bowl Sensors**	**Device 3D Structure**	**User Interface**	**Device Operation**
3	Food and water dispensers properly dispense when instructed.	Food and water bowl sensors are able to accurately measure the presence of substances within their bowls.	3D structure is aesthetically pleasing, structurally sound, and circuitry remains protected from the elements.	Screen works flawlessly, buttons correspond to intuitive actions, no system resets or outside explanations required.	The device is able to (1) dispense the correct amount of food during the correct times (2) dispense the correct amount of water during the correct times (3) maintain the water level in the water bowl
2	Food and water dispensers both dispense, but may occasionally jam or malfunction **OR** only one dispenser properly dispenses when instructed.	Food and water bowl sensors are able to measure the presence of substances within their bowls with decent accuracy **OR** one sensor is able to accurately measure the presence of a substance. within its respective bowl	3D structure is structurally sound, and circuitry remains protected from the elements, but is not aesthetically pleasing.	Still able to function, but not pleasurable to work with, e.g. buggy screen, sometimes unresponsive buttons, unintuitive layout	Device can perform 2 of the 3 requirements required to earn 3 points in "Device Operation"
1	Only one dispenser dispenses, but may occasionally jam or malfunction	One sensor is able to measure the presence of a substance within its respective bowl with relative accuracy	Circuitry remains protected from the elements, but 3D structure is not aesthetically pleasing, and not structurally sound.	Screen not working, but UI logic still present and correct, button logic functions. Requires plugging into a computer to see what should be on the screen.	Device can perform 1 of the 3 requirements required to earn 3 points in "Device Operation"

0	Neither dispenser is able to dispense	Neither sensor is able to measure the presence of substances with relative accuracy	3D structure failed to protect circuitry from the elements.	No functionality on buttons or UI logic. Screen is useless as the data displayed comes from incorrect sources. Or requires connection to PC in order to change variable values	Device can perform none of the requirements required to earn 3 points in "Device Operation"

Table 1 Grade Breakdown of Project

Adding up the scores from the different sections yields a final score of 10.5, which is a "B" letter grade as shown in Table 2.

Points	Grade
12 - 15	A
8 - 11	B
4 - 7	C
0 - 3	D

Table 2 Points to Grade Conversion Chart

Costs

In completing the Smart Pet Feeding Station, $401.01 was used to purchase device components and fabricate the PCB as shown in Table 3 Bill of Materials. Even so, this value does not represent the true cost of the device since a few additional components were purchased by members of the group, which were not factored into the presented cost. Also, the cost of the 3D printed components and the wooden structure was never specified and thus it is unknown of what the true cost of the device is.

If the device were to be manufactured, the cost of the 3D design would change since it would be made out of plastic instead of wood. Also, if units were manufactured in 10000 unit quantities, the price would certainly decrease. For example, the OLS500D3L costs $43.12 for a single unit, but costs $38.07 per unit if 100 sensors are bought in bulk.

Future Work

There are several improvements that should be made to the Smart Pet Feeding Station in future work. First, the device should implement network capabilities to allow users to control the device using their smart phone in place of an LCD screen and buttons. This would reduce the cost of the device since the LCD and buttons would not have to be purchased, and people would be able to control the device remotely. It may also be useful to have a camera on the device to verify that pets are eating and to verify that food and water are being dispensed.

The food dispenser mechanism also needs to be changed. If the circular disk is to be used in the future, it must be made thicker since food often bends the disk, allowing the food to escape the food chute. Jam detection should also be added to the system since the food dispenser stepper motor often jammed.

To make the device more hands free, the water container can be replaced by a house's main water supply, meaning that the user would not have to constantly retrieve and fill up the device's water container. The water bowl should also have a drain added to it since the bowl can not currently be removed.

References

[1] "How Much Water Should a Dog Drink? | PetMD." https://www.petmd.com/dog/nutrition/evr_dg_the_importance_of_water (accessed Sep. 10, 2021).
[2] "How Much To Feed Your Dog - Prudent Pet Insurance." https://www.prudentpet.com/how-much-should-dog-eat/ (accessed Sep. 10, 2021).
[3] A. Wortinger, *Nutrition for Veterinary Technicians and Nurses*. Somerset, UNITED STATES: John Wiley & Sons, Incorporated, 2013. Accessed: Oct. 22, 2021. [Online]. Available: http://ebookcentral.proquest.com/lib/uva/detail.action?docID=1187179
[4] "Keeping Pets (Dogs and Cats) in Homes: Phase I: Reasons for Not Owning a Dog or Cat - American Humane - American Humane." https://www.americanhumane.org/publication/keeping-pets-dogs-and-cats-in-homes-phase-i-reasons-for-not-owning-a-dog-or-cat/ (accessed Sep. 23, 2021).
[5] "WOpet Chimp II Automatic Cat & Dog Feeder WiFi 8-Meal, 8L | WOPET." https://www.wopet.com/products/wopet-chimp-4-meal-automatic-pet-feeder-7l (accessed Sep. 10, 2021).
[6] "Pet Supplies : PetSafe Drinkwell Everflow Indoor/Outdoor Dog and Cat Water Fountain, Pet Drinking Fountain, 192 oz. Water Capacity : Pet Self Waterers : Amazon.com." https://www.amazon.com/PetSafe-Drinkwell-Everflow-Fountain-Drinking/dp/B00CQ12KKO/ref=sr_1_29?dchild=1&keywords=automatic+pet+waterer&qid=1632100245&sr=8-29 (accessed Sep. 19, 2021).
[7] "MSP430FR2355 data sheet, product information and support | TI.com." https://www.ti.com/product/MSP430FR2355 (accessed Dec. 16, 2021).
[8] "MSP-EXP430FR2355 Development kit | TI.com." https://www.ti.com/tool/MSP-EXP430FR2355 (accessed Dec. 16, 2021).
[9] "What is Multisim™?" https://www.ni.com/en-us/shop/electronic-test-instrumentation/application-software-for-electronic-test-and-instrumentation-category/what-is-multisim.html (accessed Dec. 17, 2021).
[10] "Electronic Waste: How Waste Leads to Design Challenges - In Compliance Magazine." https://incompliancemag.com/article/electronic-waste-how-waste-leads-to-design-challenges/ (accessed Sep. 19, 2021).
[11] "Electricity and the environment - U.S. Energy Information Administration (EIA)." https://www.eia.gov/energyexplained/electricity/electricity-and-the-environment.php (accessed Sep. 19, 2021).
[12] "NEMA Ratings for Enclosures - NEMA Enclosure Ratings Chart (1,3, 3R, 4, 4X, 12) | Nema Enclosures." https://www.nemaenclosures.com/enclosure-ratings/nema-rated-enclosures.html (accessed Dec. 17, 2021).
[13] "IPC-2221B: Generic Standard on Printed Board Design." https://shop.ipc.org/general-electronics/standards/2221-0-b-english (accessed Sep. 17, 2021).
[14] "IPC-2222B-English: Sectional Design Standard for Rigid Organic Printed Boards." https://shop.ipc.org/general-electronics/standards/2222-0-b-english (accessed Sep. 17, 2021).
[15] "Embedded C Coding Standard | Barr Group." https://barrgroup.com/embedded-systems/books/embedded-c-coding-standard (accessed Sep. 19, 2021).
[16] "What Is VirtualBench?" https://www.ni.com/en-us/shop/electronic-test-instrumentation/virtualbench/what-is-virtualbench.html (accessed Dec. 17, 2021).

[17] “CCSTUDIO IDE, configuration, compiler or debugger | TI.com.” https://www.ti.com/tool/CCSTUDIO (accessed Dec. 17, 2021).
[18] “Build software better, together,” *GitHub*. https://github.com (accessed Dec. 17, 2021).
[19] “3D CAD Design Software | SOLIDWORKS.” https://www.solidworks.com/home-page-2021 (accessed Dec. 17, 2021).
[20] “8 Dangers of Leaving Your Dog Home Alone for Long – Top Dog Tips.” https://topdogtips.com/dangers-leaving-dog-home-alone/ (accessed Sep. 10, 2021).
[21] S. Krishnamurthy, “Automatic pet food feeder,” US6401657B1, Jun. 11, 2002 Accessed: Sep. 22, 2021. [Online]. Available: https://patents.google.com/patent/US6401657B1/en?q=automatic+dog+feeder&oq=automatic+dog+feeder
[22] S. Krishnamurthy, “Automatic pet feeder,” US7650855B2, Jan. 26, 2010 Accessed: Dec. 17, 2021. [Online]. Available: https://patents.google.com/patent/US7650855B2/en?oq=+7%2c650%2c855
[23] S. S. Willett, “Combined pet food and water dispenser,” US8245665B2, Aug. 21, 2012 Accessed: Dec. 17, 2021. [Online]. Available: https://patents.google.com/patent/US8245665B2/en?oq=+8.245%2c665
[24] “FX1901-0001-0200-L TE Connectivity Measurement Specialties | Sensors, Transducers | DigiKey.” https://www.digikey.com/en/products/detail/te-connectivity-measurement-specialties/FX1901-0001-0200-L/5277314 (accessed Dec. 10, 2021).
[25] “AD623BNZ Analog Devices Inc. | Integrated Circuits (ICs) | DigiKey.” https://www.digikey.com/en/products/detail/analog-devices-inc/AD623BNZ/760282 (accessed Dec. 10, 2021).
[26] “OLS500D3 Sensata-Cynergy3 | Sensors, Transducers | DigiKey.” https://www.digikey.com/en/products/detail/sensata-cynergy3/OLS500D3/4209084 (accessed Dec. 13, 2021).
[27] “SF2423-10B41 Sanyo Denki SanMotion Products | Motors, Solenoids, Driver Boards/Modules | DigiKey.” https://www.digikey.com/en/products/detail/sanyo-denki-sanmotion-products/SF2423-10B41/13533452 (accessed Dec. 15, 2021).
[28] “DRV8434RGER Texas Instruments | Integrated Circuits (ICs) | DigiKey.” https://www.digikey.com/en/products/detail/texas-instruments/DRV8434RGER/13562989 (accessed Dec. 16, 2021).
[29] “DRV8434RGER Texas Instruments | Integrated Circuits (ICs) | DigiKey.” https://www.digikey.com/en/products/detail/texas-instruments/DRV8434RGER/13562989?s=N4IgjCBcpmAMVQGMoDMCGAbAzgUwDQgD2UA2iAMwAscAbFRSALqEAOALlCAMrsBOASwB2AcxABfQmACsVRCBSQMOAsTIgaADgp1mbTpB79hYyeFr15i5XkIlI5CgCZqcBIWevNIDy5oBOH0o-WD0QDi5eQVEJKX9NQOgFNCxbNQcQBBZwgyNo00IAWicrKH4AV1V7cmlmM0LE5DK%2BSrt1CCZxMxKM7HZcVlZcPjDaeQEAEy5C730uIPYATyGudGwULqA (accessed Dec. 15, 2021).
[30] “1150 Adafruit Industries LLC | Maker/DIY, Educational | DigiKey.” https://www.digikey.com/en/products/detail/adafruit-industries-llc/1150/5638299 (accessed Dec. 16, 2021).
[31] “KSP2222ABU onsemi | Discrete Semiconductor Products | DigiKey.” https://www.digikey.com/en/products/detail/onsemi/KSP2222ABU/1047387 (accessed Dec. 16, 2021).

[32] “D6C90 F2 LFS C&K | Switches | DigiKey.” https://www.digikey.com/en/products/detail/c-k/D6C90-F2-LFS/1466345 (accessed Dec. 16, 2021).
[33] “UCLAMP3301H.TCT Semtech Corporation | Circuit Protection | DigiKey.” https://www.digikey.com/en/products/detail/semtech-corporation/UCLAMP3301H-TCT/1000952 (accessed Dec. 16, 2021).
[34] “ACM2004F-FL-YBW-R AZ Displays | Optoelectronics | DigiKey.” https://www.digikey.com/en/products/detail/az-displays/ACM2004F-FL-YBW-R/13984928?s=N4IgTCBcDaIIIGECyYAMqAsAxEBdAvkA (accessed Dec. 17, 2021).
[35] “PTV09A-4225F-B104 Bourns Inc. | Potentiometers, Variable Resistors | DigiKey.” https://www.digikey.com/en/products/detail/bourns-inc/PTV09A-4225F-B104/3781156 (accessed Dec. 17, 2021).
[36] “TR9CI2700CCPCIMR6B GlobTek, Inc. | Power Supplies - External/Internal (Off-Board) | DigiKey.” https://www.digikey.com/en/products/detail/globtek-inc/TR9CI2700CCPCIMR6B/9837836?s=N4IgTCBcDaICoCUCcBhAkmA7ABmylACugLIIBsAQiALoC%2BQA (accessed Dec. 16, 2021).
[37] “LT1121CZ-3.3#PBF Analog Devices Inc. | Integrated Circuits (ICs) | DigiKey.” https://www.digikey.com/en/products/detail/analog-devices-inc/LT1121CZ-3-3-PBF/890240 (accessed Dec. 16, 2021).
[38] “LT1121CZ-5#PBF Analog Devices Inc. | Integrated Circuits (ICs) | DigiKey.” https://www.digikey.com/en/products/detail/analog-devices-inc/LT1121CZ-5-PBF/894343 (accessed Dec. 16, 2021).
[39] “UA78M06CKVURG3 Texas Instruments | Integrated Circuits (ICs) | DigiKey.” https://www.digikey.com/en/products/detail/texas-instruments/UA78M06CKVURG3/1000274 (accessed Dec. 16, 2021).
[40] “MC7812CDTRKG onsemi | Integrated Circuits (ICs) | DigiKey.” https://www.digikey.com/en/products/detail/onsemi/MC7812CDTRKG/1481277?s=N4IgTCBcDaILIGEDsAOAjGBARAKgJQGkBxEAXQF8g (accessed Dec. 16, 2021).
[41] “AstroAI Multimeter 2000 Counts Digital Multimeter with DC AC Voltmeter and Ohm Volt Amp Tester ; Measures Voltage, Current, Resistance; Tests Live Wire, Continuity - - Amazon.com.” https://www.amazon.com/AstroAI-Digital-Multimeter-Voltage-Tester/dp/B01ISAMUA6 (accessed Dec. 17, 2021).
[42] “Amazon.com: Pastall 100 PCS (8 Different Sizes) Heatsink Kit with Conductive Adhesive Tape, Aluminum Heat Sink Cooler and Copper Heatsink for Raspberry Pi A B B+ 2/3/4 : Electronics.” https://www.amazon.com/Raspberry-Heatsink-Conductive-Adhesive-Aluminum/dp/B082RWXFR2/ref=sr_1_5?keywords=heatsinks&qid=1639767363&sr=8-5 (accessed Dec. 17, 2021).

Appendix

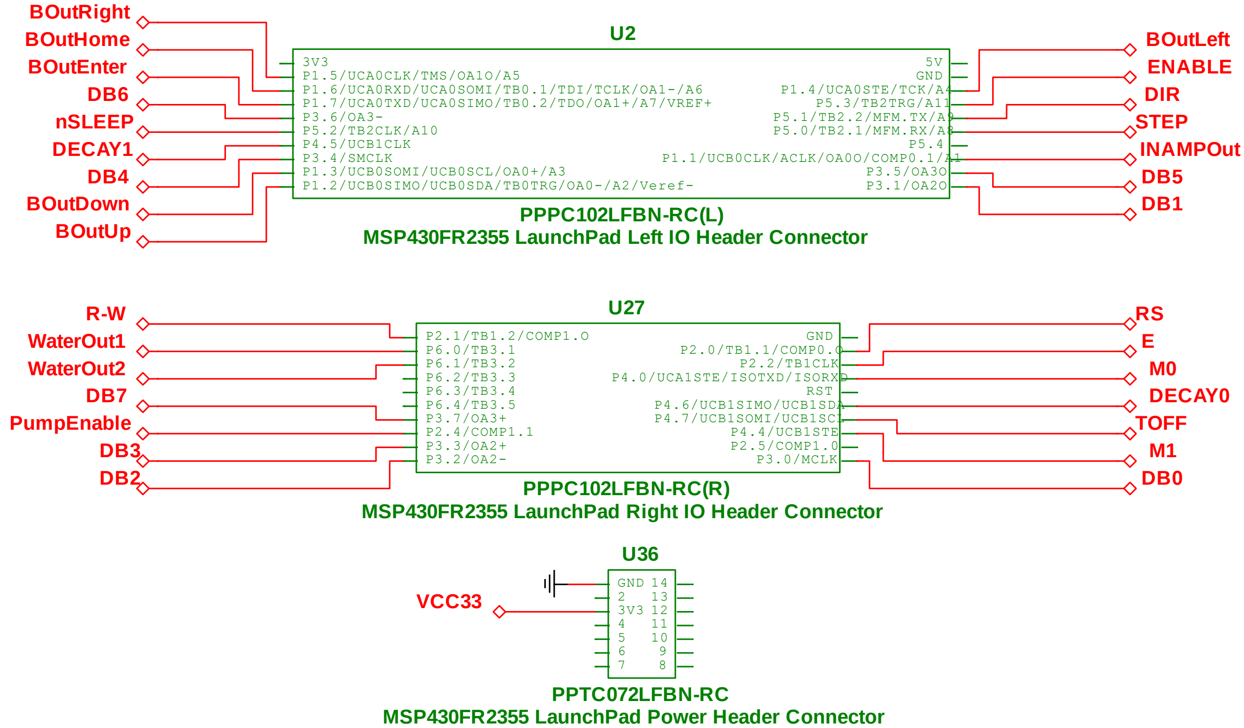

Figure 29 MSP430FR2355 Launchpad Connections Schematic

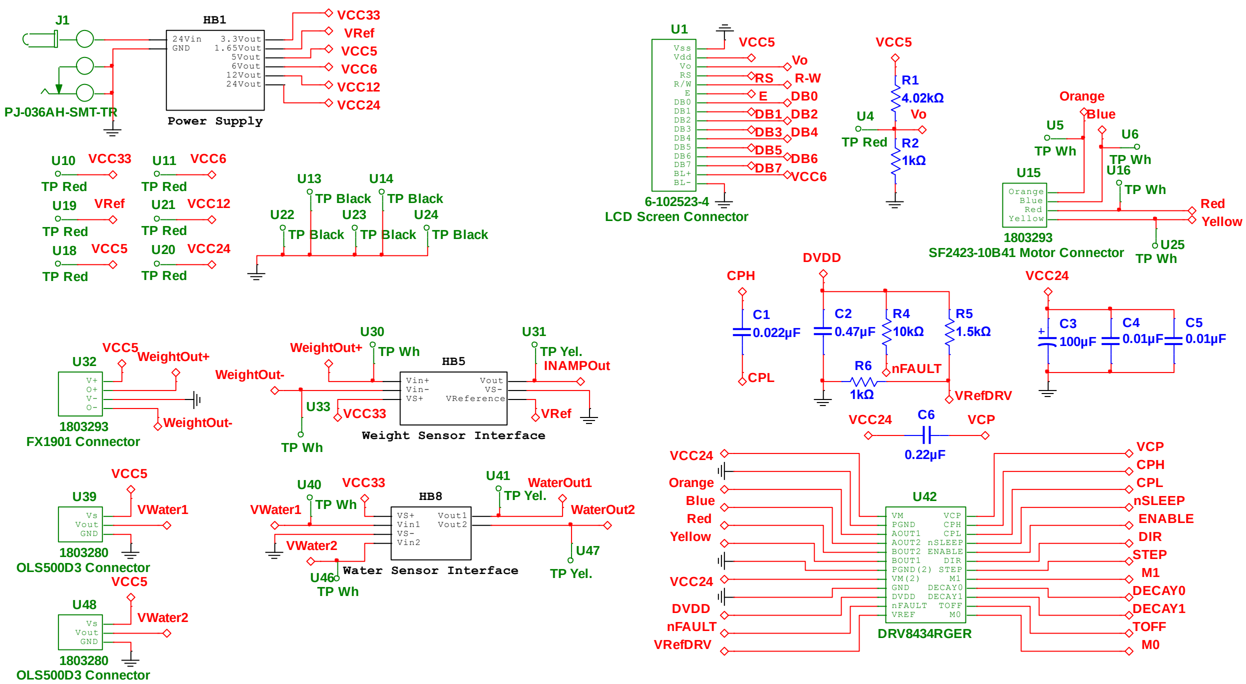

Figure 30 Smart Pet Feeding Station Full Schematics 1/2

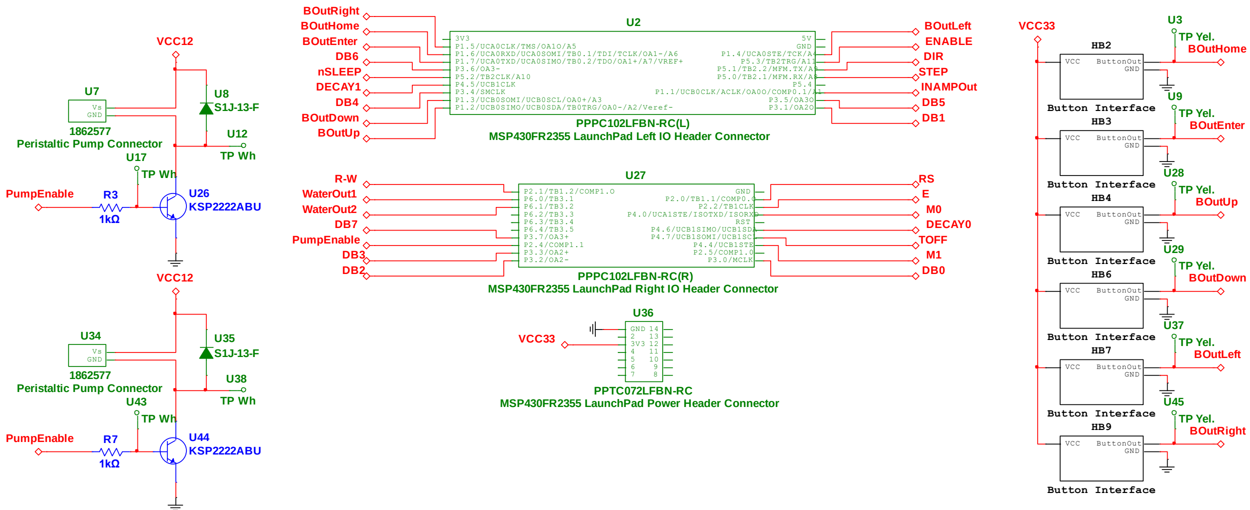

Figure 31 Smart Pet Feeding Station Full Schematics 2/2

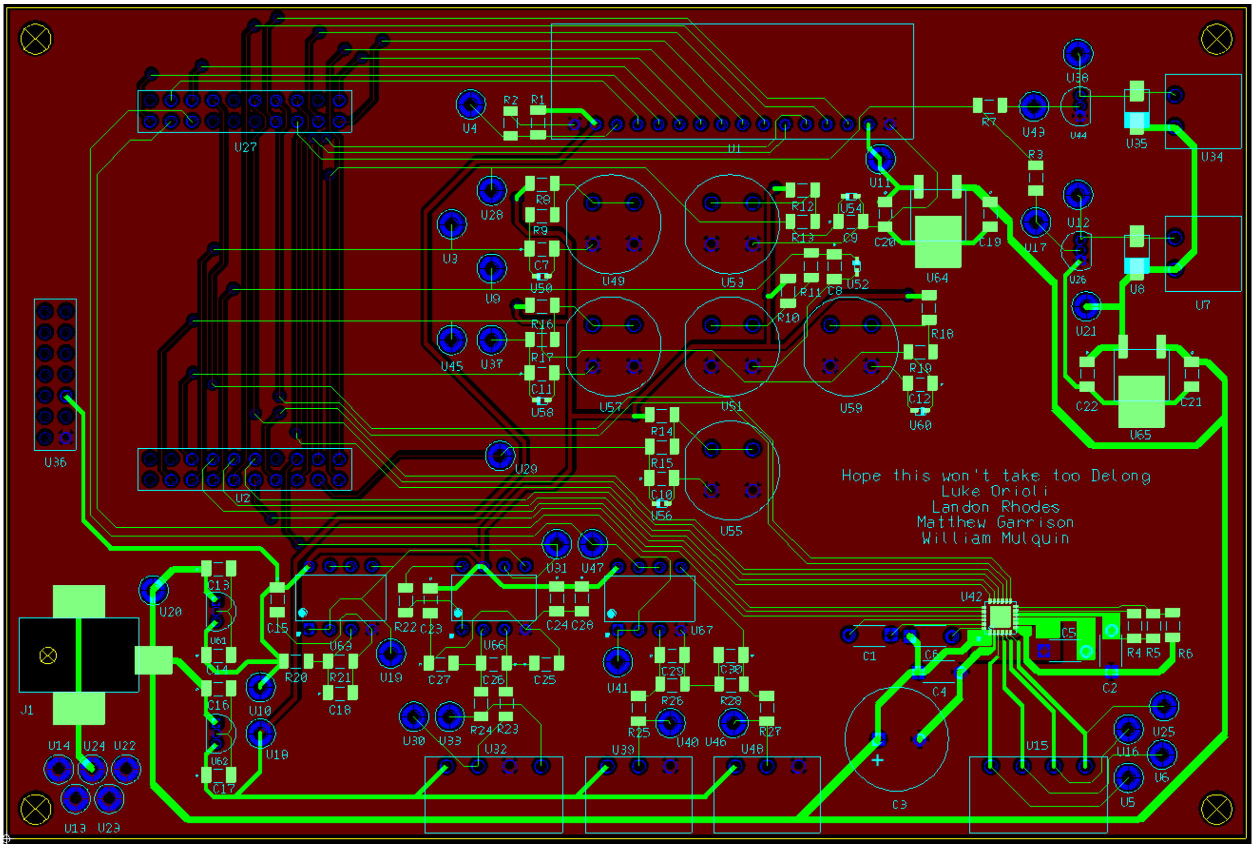

Figure 32 Smart Pet Feeding Station PCB Layout

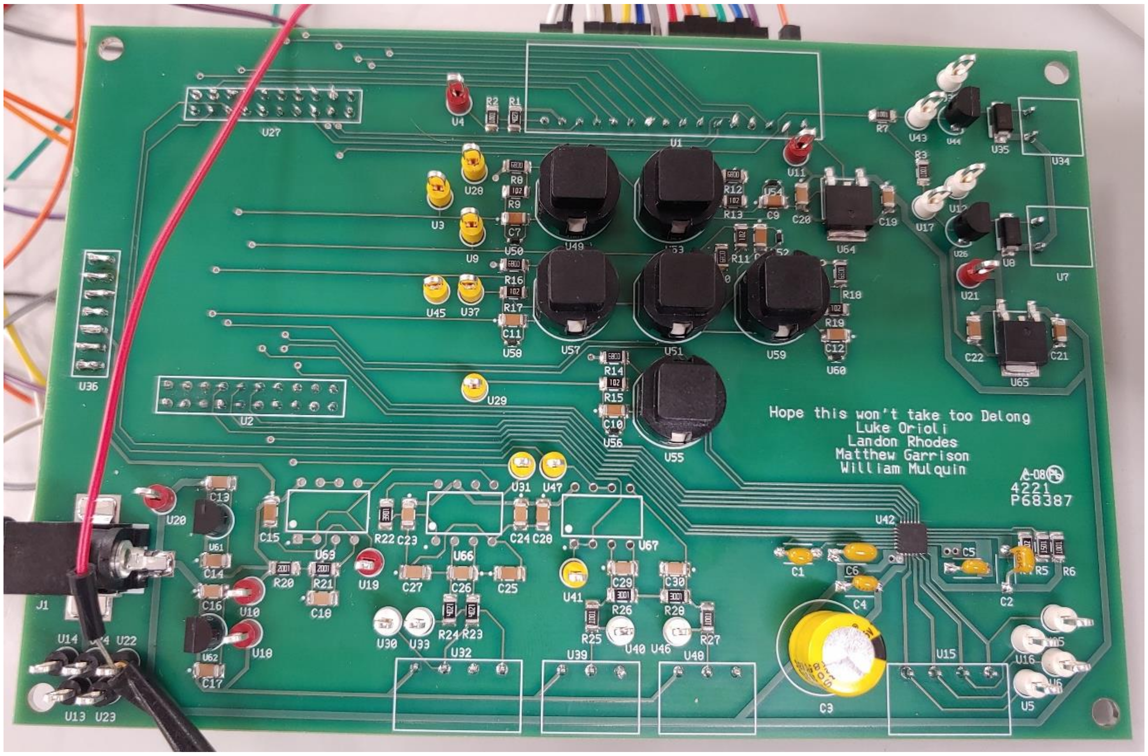

Figure 33 Smart Pet Feeding Station Populated PCB

```c
// Generic FSM type.
//
typedef struct
{
    uint32_t value;
} FSMType;

// Weight sensor FSM type.
//
typedef struct
{
    FSMType FSM;
    uint16_t weight_ADC_value;  // holds filtered measurement of sensor weight.
    uint16_t sensor_input_buffer[SENSOR_INPUT_BUFFER_LENGTH];   // stores previous sampled sensor ADC input values.
    uint16_t buffer_index;  // current position in the sensor value buffer.
    uint32_t cumulative_sum;    // cumulative sum of all elements in the sensor value buffer.
    uint16_t sensor_average;    // average value of the values in the sensor value buffer.

} WeightSensorType;

// Water sensor FSM type.
//
typedef struct
{
    FSMType FSM;
    uint8_t current_water_contact_image;
    uint8_t prev_water_contact_image;
    uint8_t water_contact_deltas;
    uint8_t water_contact_plus;
    uint8_t water_contact_minus;
    uint8_t states;

} WaterSensorsType;

// Push button FSM type.
//
typedef struct
{
    FSMType FSM;
    uint8_t current_states;
    uint8_t prev_states;
    uint8_t button_deltas;
    uint8_t button_plus;
    uint8_t button_minus;

    // Debounce eliminated states.
    //
    uint8_t prev_debounced_states;
    uint8_t current_debounced_states;
    uint8_t debounced_button_deltas;
    uint8_t button_pressed;

} PushButtonsType;
```

Figure 34 Data Structure Definitions for Weight Sensor, Water Sensor, and Push Button State Information

```c
// Parent Dispense Event
//
typedef struct
{
    uint16_t event_id;
    enum substance type;
    enum week dispense_day;
    uint32_t dispense_time;
    uint8_t active;
    uint32_t active_time;
    uint8_t completed;
    uint8_t deletable;

} DispenseEvent;

// Food dispensing event type. Inherits from the dispense event type.
//
typedef struct
{
    DispenseEvent Event;
    uint16_t food_amount;

} FeedingEvent;

// Water dispensing event type. Inherits from the dispense event type.
//
typedef struct
{
    DispenseEvent Event;
    uint8_t water_level;

} WateringEvent;

typedef struct
{
    uint8_t enable;
    uint8_t water_level;
    uint8_t active;
    uint32_t active_time;
    uint8_t contact;
    uint32_t no_contact_time;

} WaterLevelHold;
```

Figure 35 Data Structure Definitions for Dispense Events

Figure 36 Smart Pet Feeding Station

	A	B	C	D	E	F
1	Quantity	Part Number	Manufacturer Part Number	Description	Unit Price	Total Part Cost
2	1	223-1776-ND	FX1901-0001-0010-L	SENSOR TENSE LOAD CELL	32.63	32.63
3	2	725-1284-ND	OLS500D3	OPT LIQUID LVL SENSOR M10 MNT HI	43.12	86.24
4	1	AD623BNZ-ND	AD623BNZ	IC INST AMP 1 CIRCUIT 8DIP	10.77	10.77
5	2	S6106-ND	PPPC102LFBN-RC	CONN HDR 20POS 0.1 GOLD PCB	1.26	2.52
6	2	277-1207-ND	1803280	TERM BLOCK HDR 3POS 90DEG 3.81MM	1.32	2.64
7	2	277-11344-ND	5447874	TERM BLOCK PLUG 3POS STR 3.81MM	3.58	7.16
8	2	LMC6482IN/NOPB-ND	LMC6482IN/NOPB	IC OPAMP GP 2 CIRCUIT 8DIP	5.99	11.98
9	1	3387-ACM2004F-FL-YBW-R-ND	ACM2004F-FL-YBW-R	DISPLAY LCD CHARACTER 20X4 MONOC	30.56	30.56
10	2	A33031-ND	6-102523-4	CONN HEADER R/A 16POS 2.54MM	5.72	11.44
11	12	401-1988-ND	D6C90 F2 LFS	SWITCH PUSH SPST-NO 0.1A 32V	1.001	12.012
12	1	296-DRV8434RGERCT-ND	DRV8434RGER	48-V, 2.5-A BIPOLAR STEPPER MOTO	4.57	4.57
13	1	2300-SF2423-10B41-ND	SF2423-10B41	STEP, F2, SQ.42, 1.8, , , BIPOLA	27.5	27.5
14	1	296-50211-ND	MSP-EXP430FR2355	LAUNCHPAD MSP430FR2355 EVAL BRD	15.59	15.59
15	2	277-1206-ND	1803277	TERM BLOCK HDR 2POS 90DEG 3.81MM	0.86	1.72
16	2	277-14221-ND	1851999	TERM BLOCK PLUG 2POS STR 3.81MM	3.86	7.72
17	2	S1J-FDICT-ND	S1J-13-F	DIODE GEN PURP 600V 1A SMA	0.27	0.54
18	2	277-1208-ND	1803293	TERM BLOCK HDR 4POS 90DEG 3.81MM	1.79	3.58
19	2	277-11345-ND	5447887	TERM BLOCK PLUG 4POS STR 3.81MM	4.76	9.52
20	2	KSP2222ABUFS-ND	KSP2222ABU	TRANS NPN 40V 600MA TO92-3	0.41	0.82
21	1	S7075-ND	PPTC072LFBN-RC	CONN HDR 14POS 0.1 TIN PCB	0.93	0.93
22	6	UCLAMP3301HCT-ND	UCLAMP3301H.TCT	TVS DIODE 3.3VWM 8VC SOD523	0.7	4.2
23	1	LT1121CZ-3.3#PBF-ND	LT1121CZ-3.3#PBF	IC REG LINEAR 3.3V 150MA TO92-3	4.02	4.02
24	1	LT1121CZ-5#PBF-ND	LT1121CZ-5#PBF	IC REG LINEAR 5V 150MA TO92-3	4.02	4.02
25	1	296-19532-1-ND	UA78M06CKVURG3	IC REG LINEAR 6V 500MA TO252-3	0.7	0.7
26	1	CP-036AHPJCT-ND	PJ-036AH-SMT-TR	CONN PWR JACK 2X5.5MM SOLDER	1.36	1.36
27	1	1939-1771-ND	TR9CI2700CCPCIMR6B	AC/DC DESKTOP ADAPTER 24V 65W	23.06	23.06
28	7	36-5010-ND	5010	PC TEST POINT MULTIPURPOSE RED	0.42	2.94
29	5	36-5011-ND	5011	PC TEST POINT MULTIPURPOSE BLACK	0.42	2.1
30	9	36-5014-ND	5014	PC TEST POINT MULTI PURP YELLOW	0.42	3.78
31	12	36-5012-ND	5012	PC TEST POINT MULTIPURPOSE WHITE	0.42	5.04
32	1	399-4169-ND	C315C223K5R5TA	CAP CER 0.022UF 50V X7R RADIAL	0.36	0.36
33	1	399-14039-1-ND	C315C474K5R5TA7303	CAP CER 0.47UF 50V X7R RADIAL	0.38	0.38
34	1	1572-1306-ND	107RSS035M	CAP ALUM 100UF 20% 35V RADIAL	0.59	0.59
35	1	399-13990-1-ND	C322C224K5R5TA7301	CAP CER 0.22UF 50V X7R RADIAL	0.39	0.39
36	10	399-7009-1-ND	C1206C104K5RACAUTO	CAP CER 0.1UF 50V X7R 1206	0.127	1.27
37	3	399-17491-1-ND	C1206X334K5RAC7800	CAP CER 0.33UF 50V X7R 1206	0.82	2.46
38	2	399-20223-1-ND	C1206C102J5RACAUTO	CAP CER 1000PF 50V X7R 1206	0.2	0.4
39	2	399-20223-1-ND	C1206C102J5RACAUTO	CAP CER 1000PF 50V X7R 1206	0.2	0.4
40	2	399-14008-1-ND	C322C103K5R5TA7301	CAP CER 10000PF 50V X7R RADIAL	0.37	0.74
41	1	13-RT1206BRD07400RLCT-ND	RT1206BRD07400RL	RES SMD 400 OHM 0.1% 1/4W 1206	0.65	0.65
42	10	YAG6061CT-ND	SR1206JR-7W1KL	RES SMD 1K OHM 5% 1/2W 1206	0.451	4.51
43	6	13-RT1206FRE07680RLCT-ND	RT1206FRE07680RL	RES SMD 680 OHM 1% 1/4W 1206	0.14	0.84
44	2	13-AF1206FR-072KLCT-ND	AF1206FR-072KL	RES SMD 2K OHM 1% 1/4W 1206	0.17	0.34
45	2	311-3.00KFRCT-ND	RC1206FR-073KL	RES 3K OHM 1% 1/4W 1206	0.1	0.2
46	3	311-4.02KFRCT-ND	RC1206FR-074K02L	RES 4.02K OHM 1% 1/4W 1206	0.1	0.3
47	1	13-AC1206FR-073K9LCT-ND	AC1206FR-073K9L	RES SMD 3.9K OHM 1% 1/4W 1206	0.1	0.1
48	1	MC7812CDTRKGOSCT-ND	MC7812CDTRKG	IC REG LINEAR 12V 1A DPAK	0.77	0.77
49	1	PCB Board	-	-	33	33
50	1	RMCF1206FT1K50CT-ND	RMCF1206FT1K50	RES 1.5K OHM 1% 1/4W 1206	0.1	0.1
51	1	RMCF1206FT10K0CT-ND	RMCF1206FT10K0	RES 10K OHM 1% 1/4W 1206	0.1	0.1
52	1	RMCF1206FG49K9CT-ND	RMCF1206FG49K9	RES 49.9K OHM 1% 1/4W 1206	0.1	0.1
53	1	455-1369-ND	BHR-04VS-1	CONN HOUSING BH 4POS 4.0MM	0.28	0.28
54	10	RMCF1206FT1K00CT-ND	RMCF1206FT1K00	RES 1K OHM 1% 1/4W 1206	0.036	0.36
55	2	399-7009-1-ND	C1206C104K5RACAUTO	CAP CER 0.1UF 50V X7R 1206	0.18	0.36
56	1	SAM9041-ND	IDSS-16-D-05.00-G	CABLE ASSEM .1" 16POS F-F 5"	11.36	11.36
57	1	339-C1206C473M5RAC7800CT-ND	C1206C473M5RAC7800	CAP CER 0.047UF 50V X7R 1206	0.21	0.21
58	10	339-C1206C103K1RAC7800CT-ND	C1206C103K1RAC7800	CAP CER 10000PF 100V X7R 1206	0.129	1.29
59	1	2183-1203-ND	1203	5MM SHAFT #4-40 HLS 2PK MNTG HUB	7.49	7.49
60					Subtotal	401.012

Table 3 Bill of Materials