ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

Automatic Cat Litter Box

Team 12
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Contents

Introduction

1.1 Problem

Modern automatic cat litter boxes neglect the crucial issue of odor control and often lack the capability to track the duration and frequency of a cat's litter box usage. Over time, as these systems accumulate waste, odors can intensify, causing discomfort for both cats and owners. Given cats' highly sensitive sense of smell, they detect these odors well before humans do. Without monitoring their habits, changes in litter box behavior such as prolonged visits or increased frequency may be missed, which can indicate potential health concerns such as urinary tract infections or digestive issues. These oversights can create an unpleasant living environment, pose health concerns, reduce usability and contribute to stress and anxiety.

1.2 Solution

The proposed solution centers around a cat litter box with a motorized raking mechanism for scooping. The motor will control a pulley system that directs the rake through the entire length of the litter box. Weight sensors will be positioned beneath the litter box. These sensors are responsible for initiating the motorized raking process upon detecting the entry and exit of the cat. Beyond triggering the raking process, these sensors will also act as the means to monitor the cat. By continuously capturing data, they quantify the duration of each cat visit, the frequency of visits and the weight of the cat itself. Odor sensors will be placed within the hood of the litter box, designed to detect and monitor the buildup of ammonia in real-time. This information will be communicated to the user through their phone. The connection between the litter box and the user's phone will be via Bluetooth. The user will also be able to control the raking through the phone.

1.3 Visual Aid

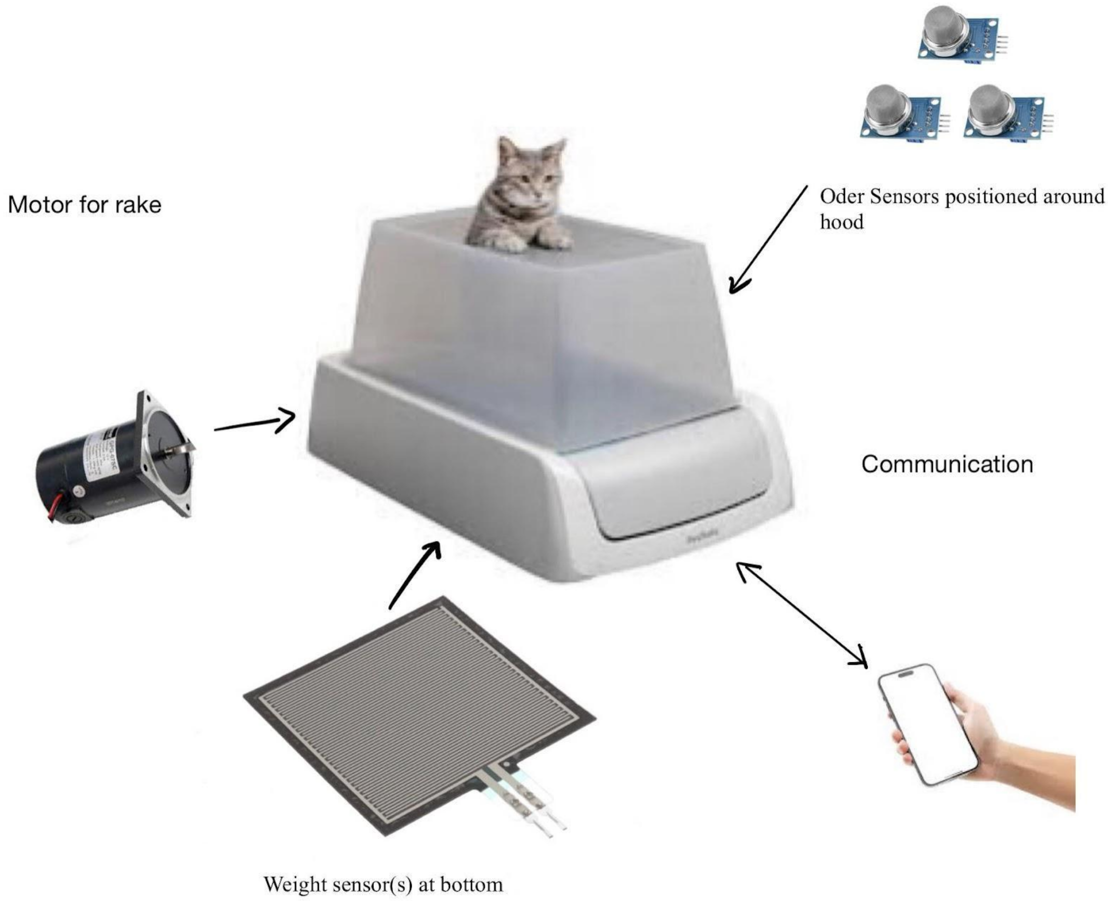

Figure 1: Visual Aid

For the physical design, we are cooperating with the ECE Machine Shop. Together We came up with a rough draft of how the automatic litter box should be set up. We decided to keep it at that and give them the creative liberty to adjust how they see fit, as they are experienced professionals.

1.4 High-level requirements list

- The litter box should accurately detect the cat's weight, frequency of use, and the duration with an accuracy of 70% or higher.
- The rake should be able to rake the majority of waste into the disposal area (>70%).
- The user should be notified in a timely manner, within 5 minutes from the detection of the sensors, while the user's phone is within Bluetooth range (7-10m).

Design

2.1 Block Diagram

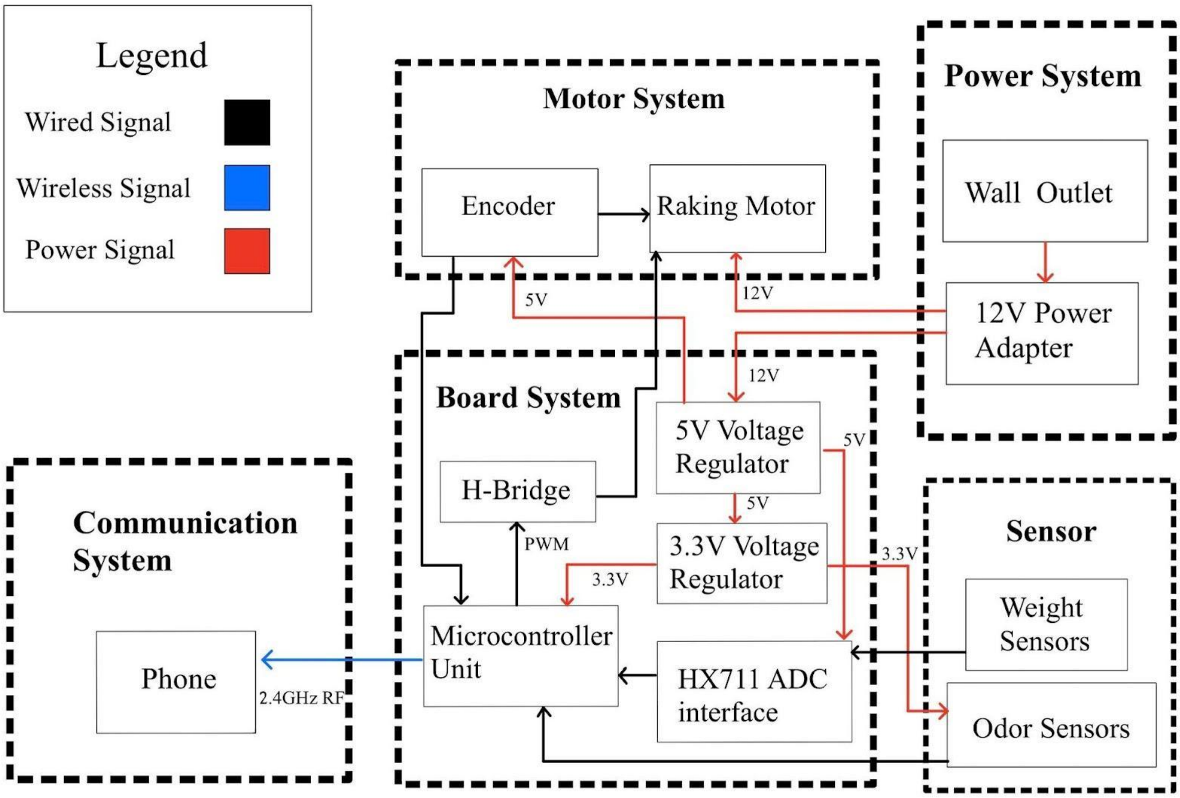

Figure 2: Block Diagram

2.2 Subsystem Description

Board Subsystem:

This subsystem has an ESP32-C3FN4 microcontroller SoC as the core, and will have any needed components attached(antenna, H-bridge, voltage regulators, etc). It will be used for connecting and interfacing with the motors, sensors and the user. Below is the draft of the schematic for the PCB.

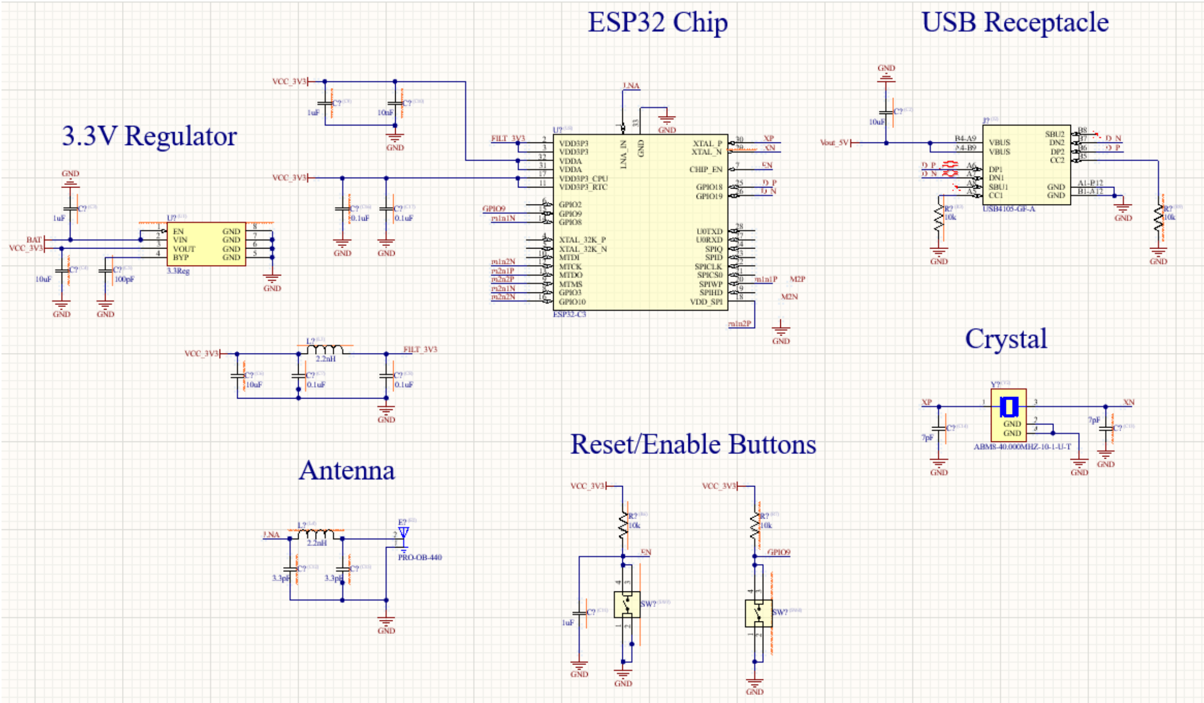

Figure 3: Draft of Schematic

Motor Subsystem:

This subsystem bridges the functionality of the code and data to the physical litter box. It is directly controlled by the MCU. It is attached to the rake through a pulley system for cleaning the litter box. The rake and the pulley system will be attached on a stand around the litter box.

Sensor Subsystem:

This subsystem gives the MCU the signal to start the cleaning process to ensure a tidy litter box. It is also the sole provider of any information collected concerning the health of the cat and the state of the litter box. The weight sensors will need to be recalibrated after every visit from the cat to ensure the loss of litter will not affect the accuracy. The weight sensors will be placed at the bottom of our entire system, so the entire weight of the system will be measured at all times.

Communication Subsystem:

This subsystem allows for the notification to the user. It communicates and transmits data from the MCU to the phone, giving insight to anything the user may need to know through bluetooth

Power Subsystem:

This subsystem will take incoming AC voltage and transform it to DC voltage at 12V, ensuring safe and stable power throughout the litter box for every component that needs it. Voltage and current ratings will have to be sufficient for the motors, board components, sensors to be used together. Voltage regulators will be used to supply different voltage levels for corresponding components.

2.3 Subsystem Requirement

2.3.1 Board Subsystem

Antenna

Requirement	**Verification**
R1. The 2.4GHz antenna for BLE should be efficient enough so that when transmitting at 9dBm, the phone can stay connected to the ESP32 BLE server within 10 meters.	V1. Set up the ESP32-C3 as a BLE server and connect to it through the phone app. Walk around and record RSSI at different distances from 1-15m.
R2. The antenna must not interfere with other nearby 2.4GHz devices.	V2. Operate ESP32-C3 with the antenna near other 2.4GHz devices. Ensure no significant interference.
R3. The antenna should not obstruct or interfere with other components on the PCB.	V3. Run the sensors and motors while transmitting continuous packets and check if any packet is corrupted.

H-bridge

Requirement	**Verification**
R1. The H-bridge must provide bidirectional control of the 12-V DC motor.	V1. Use GPIO on ESP32 to verify that the H-bridge can change the motor's direction of rotation (forward and reverse).
R2. The H-bridge should be capable of handling a continuous current of at least 1A, and a peak current of at least 1.3A.	V2. Run the motor through the H-bridge for normal raking (current < 1A), then stall the motor for a few seconds (current=1.3A). Verify that the H-bridge remains functional.
R3. The H-bridge must have overcurrent protection to prevent damage to the motor and circuitry.	V3. Conduct a test by intentionally causing a continuous motor stall. Ensure that the H-bridge detects the overcurrent condition and activates protection mechanisms.

Voltage Regulator

Requirement	**Verification**
R1. The voltage regulators must output a stable 3.3V, 5V supply voltage within ±5% tolerance.	V1. Measure the output voltage of the regulator under load conditions and ensure it remains stable at 3.3V, 5V ±5%.
R2. The voltage regulator must output a stable current over 0.5A and under 1.5A for the MCU and weight sensor.	V2. Run the ESP32-C3 and weight sensor at the same time and measure the output current to make sure it is stable.
R3. The voltage regulator should have a maximum dropout voltage of 1.5V at full load.	V3. Measure the input voltage and output voltage of the regulator under full load. Ensure the dropout voltage does not exceed 1.5V.

2.3.2 Motor Subsystem

Raking Motor

Requirement	Verification
R1. The encoder must provide accurate motor positioning information. The accuracy should be at least 70%.	V1. Command the motor to specific positions and compare actual position data from the encoder to the commanded positions. Make sure the difference is within 70%.
R2. The motor torque must be sufficient to move the comb through sand.	V2. Place the comb in a tray of sand. Measure the motor's ability to move the comb through the sand with a load.
R3. The motor must have a mechanism to prevent comb jamming or blockages during operation.	V3. Run the raking process and intentionally block the comb halfway. Make sure the motor doesn't stall and draw excessive current.

2.3.3 Sensor Subsystem

Weight Sensor

Requirement	Verification
R1. The weight sensor must support a minimum weight of 25kg.	V1. Apply known weights incrementally up to 25kg on the sensor and confirm accurate weight measurement within ±5% tolerance.
R2. The weight sensor must provide a minimum resolution of 100g.	V2. Apply incremental loads and verify that the sensor detects weight changes in increments of 100g or finer.
R3. The weight sensor must have calibration functionality.	V3. Calibrate the sensor and verify that it produces accurate weight readings after calibration.

Odor Sensor

Requirement	Verification
R1. The odor sensor must provide accurate and reliable odor detection.	V1. Verify that the sensor can differentiate between environments with known odor sources and without odor.
R2. The odor sensor must operate effectively in a humid environment with 80% RH.	V2. Add water to the sand in the litter box. Verify that the sensor continues to provide consistent and accurate odor readings.
R3. The sensor must be positioned optimally within the litter box for maximum odor exposure.	V3. Position the sensor at different locations within the litter box and measure its ability to detect odors accurately. Determine the optimal sensor placement for maximum exposure to litter box odors.

2.3.4 Communication Subsystem

Requirement	Verification
R1. The communication system must reliably maintain a range of approximately 10 meters at 9dBm transmit power.	V1. Perform range tests by placing the ESP32-C3 with the communication system and a paired phone app at varying distances from 1 to 15 meters. Confirm stable communication at 10 meters.
R2. The system must provide timely notifications within 5 minutes to the phone app upon detecting excessive odor or litter box use.	V2. Simulate odor or litter box use events using odor sources/weights, and verify that the system sends notifications to the paired phone app within 5 minutes.
R3. The sensor readings should be transmitted after being packed into a standardized structure such as GATT for compatibility[1]	V3. Use a generic Bluetooth scanner app to scan the ESP32 device and verify that the transmitted sensor readings are correct in value/format.

2.3.5 Power Subsystem

12V Power Adapter

Requirement	Verification
R1. The voltage adapter must provide a stable 12V output with an error of less than 5%.	V1. Measure the output voltage of the adapter under load conditions and ensure it remains stable at 12V ±5%.
R2. The adapter must consistently provide a minimum current output of 5A.	V2. Apply a load of 5A or greater to the adapter and confirm it consistently delivers the required current without significant voltage drop.
R3. The adapter must include surge protection to safeguard connected devices from voltage spikes.	V3. Simulate voltage spikes or surges and verify that the surge protection feature effectively safeguards connected devices by preventing voltage spikes from reaching them.

2.4 Tolerance Analysis

The odor sensor's reliability is influenced by multiple factors. Commonly for an ammonia sensor, its manufacturer-rated accuracy is ±10ppm within a 0-100ppm range. Fluctuating humidity levels can compound this inconsistency, potentially introducing an additional deviation of up to ±25ppm. Furthermore, there's a natural degradation over its lifecycle, leading to a potential error of ±12ppm over a year. Collectively, when these potential errors are considered, the sensor's reading might exhibit a significant total deviation of up to ±47ppm under certain conditions.

To counter these challenges, regular calibration can be used to counteract both the sensor's inherent degradation and any external inconsistencies. Employing sensor redundancy, such as using multiple sensors and averaging their readings or maintaining a backup, can significantly improve measurement reliability. It's also beneficial to position the litter box in areas with stable humidity to reduce fluctuation-induced errors. We will implement these strategies for consistent and dependable performance.

The wall outlet delivers 120V, significantly higher than the rated voltages for the ESP32 microcontroller, sensors, and the motor. As such, a 12V power adapter is necessary. Moreover, due to varying operating voltages for our components — the ESP32 and odor sensor at 3.3V, and the weight sensor at 5V — additional voltage regulator is required. We've selected the LM317 for this purpose, given its flexibility in voltage adjustment.

The LM317 comes with three pins: Adjust, Input, and Output. It can deliver an output current ranging from 0.01 to 1.5A, with output voltages from 1.25 to 37V. For optimal operation, the voltage difference between the Input and Output pins should range from 3 to 40V. Thus, the 12V from the power adapter is fed to the Input pin. The schematic of the LM317 is illustrated in the figure below.[2]

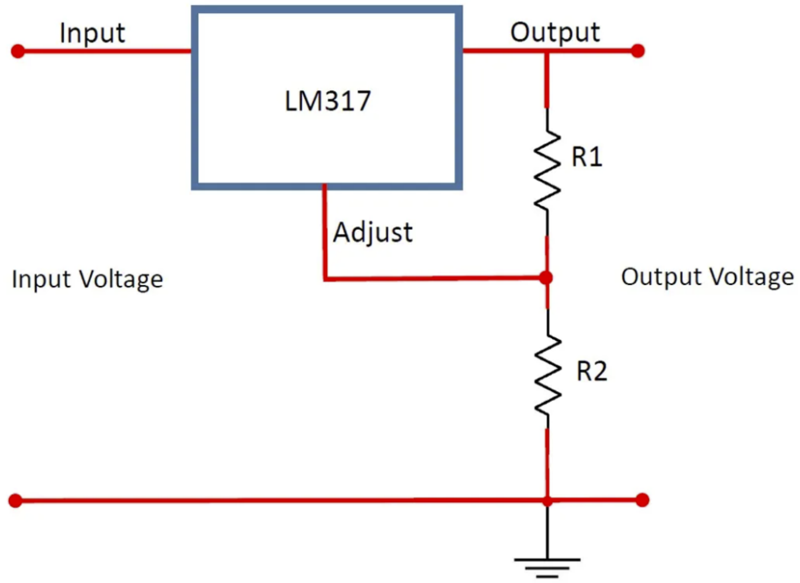

Figure 4: LM317 Circuit

The output voltage for the LM317 can be derived from:

$$Vout = Vref(1 + \frac{R2}{R1}) + (I_{ADJ} * R_2) \tag{1}$$

Given that Vref is a constant 1.25V, and I_{ADJ} (the current through the adjust pin) is 50 micro amps — negligible for our calculations — the equation simplifies to:

$$Vout = 1.25(1 + \frac{R_2}{R_1}) \tag{2}$$

Using this formula, we can determine the ratio of R2 to R1 to achieve the desired output voltages:

$$Vout = 3.3V \rightarrow \frac{R_2}{R_1} = \frac{3.3}{1.25} - 1 = 1.48 \tag{3}$$

$$Vout = 5V \rightarrow \frac{R_2}{R_1} = \frac{5}{1.25} - 1 = 3 \tag{4}$$

By selecting appropriate R1 and R2 values, we can achieve any required output voltage. For instance, for a 5V output, R1 can be 240 Ω and R2 can be 720 Ω.

Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor Costs

The average starting salary of a UIUC electrical engineer grad was $87,769[3], which is around $42/hour. We have three members dedicating around 15 hours per week, for 12 weeks. The labor cost for our group is then **$37,800**:

$$\$42/hr \times 10\frac{hr}{week} \times 12\,week \times 3\,persons \times 2.5(miscellaneous\ multiplier) = \$37,800$$

We also asked the machine shop for help with our mechanical design. We will assume it takes one work week for two people to finish our design at $30/hr. The cost of the parts required by the machine shop will be simplified with a 2.5 multiplier. The labor cost for the machine shop is then **$6,000**:

$$\$30/hr \times 8\frac{hr}{day} \times 5\,day \times 2\,persons \times 2.5(miscellaneous\ multiplier) = \$6,000$$

3.1.2 Part Costs

Description	Manufacturer	Part #	Quantity	Total Cost ($)
Stainless Steel Cat Litter Box	Kichwit	N/A	1	39.99
DC Gear Motor 12V Low Speed 10RPM Encoder Metal Gearmotor with Channel Encoder	Bemonoc	N/A	2	29.79
12V 5A Power Adapter	Velain	N/A	1	10.98
CONN RCP USB2.0 TYP C 24P SMD RA	GCT	USB4105-GF-A	1	0.81
RF TXRX MODULE BT PCB TRACE SMD	Espressif Systems	ESP32-C3-MINI-1-H4	1	1.9

DRV8874 H-BRIDGE MOTOR DRIVER	Texas Instruments	DRV8874PWPR	1	3.39
DIYmalls 4pcs Load Cell 50kg Half Bridge Strain Gauge Human Body Digital Scale Weight Sensor + HX711 Amplifier AD Module Set	DIYMalls	N/A	1	7.99
IC REG LIN POS ADJ 1.5A SOT223-4	Texas Instruments	LM317DCYR	2	1.6
40MHz Crystal	Abracon LLC	ABM8-40.000MHZ-10-1-U-T	1	1.03
Miscellaneous Resistors	N/A	N/A	~20	~5
Miscellaneous Capacitors	N/A	N/A	~30	~10
Miscellaneous Board Elements and Spare Components(Extra orders, Buttons, power receptacle, etc)	N/A	N/A	N/A	~10
Taxes + Delivery Fees (Assume 10% of above costs)	N/A	N/A		~12
				$134.48

The total cost of this project will be the sum of the labor cost and part cost:

$$\$37,800 + \$6,000 + \$135 = \$43,935$$

The total cost will be **$43,935**.

3.2 Schedule

Week	**Task**	**Person**
9/25 - 10/1	Design review sign-up	All
	Make a sketch for litter box dimensions for machine shop	All
	Purchase hardware parts	All
10/2 - 10/8	Design review	All
	Purchase electronic parts	All
	Work on PCB design	Jonathan
	Research on ESP32 programming	Shihua & Michael
10/9 - 10/15	Teamwork Evaluation I	All
	Finalize PCB design	Jonathan
	Work on driver for SPI interface to read weight sensor readings	Shihua
	Work on GPIO driver to control motors	Michael
10/16 - 10/22	Complete PCB order	All
	Test SPI driver with dev kit and weight sensor on breadboard	Shihua
	Test PCB functionality	Jonathan
	Test GPIO driver for motor control on PCB	Michael
10/23 - 10/29	Individual Progress Report	All
	Make changes to PCB should there be any issue, and order new PCB if necessary	Jonathan
	Work on driver for ADC on ESP32-C3 for odor sensor readings	Michael
	Work on driver for	Shihua

	Bluetooth on ESP32-C3 for communication subsystem	
10/30 - 11/5	Test ADC driver by connecting odor sensors and read sensor value in different environments	Michael
	Test Bluetooth driver by trying to connect to phone and sending packets	Shihua
11/6 - 11/12	Finish subsystem drivers and integrate the drivers to the main program	Shihua & Michael
	Test system hardware functionality on litter box	Jonathan
	Finalize and prepare for mock demo	All
11/13 - 11/19	Mock demo	All
	Do final amendments to the project if necessary	All
	Team contract fulfillment	All
11/27 - 12/3	Final Demo	All
	Mock Presentation	All
	Prepare for final presentation	All

Ethics and Safety

4.1 Ethics:

Our project, guided by the IEEE Code of Ethics, emphasizes safety, integrity, and respect at every step.

Our top priority is the safety of both humans and cats. Every design choice will prioritize eliminating hazards, and we're committed to sustainable development practices.

We welcome honest feedback and will promptly correct any errors. Every team member's contribution is valued, ensuring a collaborative effort. Everyone involved is treated with respect, and we have zero tolerance for any form of discrimination or harassment.

We aim to maintain these ethical standards throughout the project and expect our colleagues to do the same, ensuring a supportive and ethical working environment.[4]

4.2 Safety

Stepping down voltage from 110V to 12V poses a risk of electrical shocks or fires if not executed properly. We'll address this by utilizing a certified and adequately insulated transformer or switching power supply designed for safe voltage step-down, and ensuring proper isolation between high voltage and low voltage components to prevent failures and hazards.

Given the moving parts in the automatic litter box, there is potential for pinching, crushing, or trapping hazards. Therefore, the design will prioritize rounded edges and smooth motion mechanics to minimize risk. We will use sensors to detect if a cat is in the box, pausing or stopping the raking mechanism as necessary.

During the development phase, lab safety is crucial. We will make sure to use necessary PPE when working with tools and components. We will also ensure a clutter-free workspace, regular checks on equipment, and proper waste disposal methods.

References

[1] Espressif Systems, "ESP32-C3 Datasheet: Wi-Fi & Bluetooth LE 5.0 MCU," Espressif Systems, 2021. [Online]. Available: https://www.espressif.com/sites/default/files/documentation/esp32-c3_datasheet_en.pdf [Accessed: 09/26/2023]

[2] Texas Instruments, "LM317 3-Terminal Adjustable Regulator," Texas Instruments, 2020, [Online]. Available: https://www.ti.com/lit/ds/symlink/lm317.pdf. [Accessed: 09/26/2023]

[3] “Salary Averages,” ECE ILLINOIS. Available: https://ece.illinois.edu/admissions/why-ece/salary-averages [Accessed: 09/28/2023]

[4] "IEEE Code of Ethics," IEEE, [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 09/24/2023].