ZJU-UIUC Institute

ECE 445 / ME470

SENIOR DESIGN LABORATORY

Final Report V1.0

Intelligent Pour-over Coffee Machine

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Contents

Abstract

This report presents the development of an **Intelligent Pour-Over Coffee Machine**, a senior design project aimed at automating the coffee brewing process to replicate professional barista techniques. The system, controlled by a Raspberry Pi 5, integrates 7 subsystems including brewing, pumping, heating, sensing and user interface. Besides open-loop control over the coffee brewing, we involves factors such as temperature, pH, and weight sensors to ensure the coffee's quality and consistency. With fully unit test and whole-system verification, our system can produce good coffee. The project highlights the potential for further advances in automated coffee market, showing a blend of truth-seeking innovation and learning by labor.

Keywords: pour-over coffee, automated coffee brewing, coffee machine, sensory experience, market opportunity

1 Introduction

1.1 Background

Dating back to the early 20th century, the art of pour-over coffee has evolved from Melitta Bentz's simple paper filter to a globally handy craft tide [1]. Although this brewing method is highly praised for the complex flavor and creative experience, it is hard to maintain consistent quality for the public.

Modern consumers demand coffee that is not only good, but also convenient to drink [2]. This project proposes an **intelligent pour-over coffee machine** that employs pre-trained imitation learning algorithms. Our design aims to blend the hand-made art of pour-over with the precision of automation, contributing to the dynamic and expanding coffee machine market [3].

1.2 Problem and Solution Overview

1.2.1 Problem

The art of pour-over coffee brewing, famous for its complex flavor and high quality, is heavily dependent on the skills and experience of a barista. This craftsmanship leads to variability in coffee quality due to human element. Additionally, it is challenging for **common coffee enthusiasts** to replicate professional barista techniques *at home or in non-specialized settings,* particularly in areas where specialty coffee culture is less developed.

1.2.2 Solution

Imagine a coffee machine that automates the process of pouring water. It can customize each cup according to **the type of coffee bean and the desired flavor**. With the bean grounded and filter in place, the user can start the process with the press of a simple button, after which the machine dynamically adjusts its operations to create a delightful cup of coffee.

This machine should deliver sensory pleasure and the similar taste of hand-poured coffee, while saving time and effort. This machine is designed to mimic the skills of the master and conveniently deliver high quality in-place coffee. Fig 1 is our latest version of system (Version 3), showing the mechanical design and the feasibility of various details, with special attention to the **brewing** and **control subsystems**. Each subsystems are labeled in 2.

1.3 Visual Aid

1.3.1 Physical Design Diagram

The physical design diagram of our design is shown in Fig 1. As the figure indicates, it consists of several key components and subsystems, each serving a specific function in the brewing process, here I offer an outlined introduction of the system and a more detailed description will be expanded in section 2.2.

First is the Coffee Bean Weighing module, here a piezoresistor placed beneath the coffee bean filter detects the weight of the coffee beans as they're poured into the filter. This weight serves as input for the system's controller, which calculates optimal brewing conditions such as temperature, radius, and waiting time. Then a Cold Reservoir holds the water before it's pumped into the heating system. Once the program is runned, the cold water pump will pump water up into the Heating System, the procedure is controlled by an Arduino or STEM 32-based breadboard. The heating system consists of a container made from thermal insulation material to withstand high temperatures. A heating block, controlled by the STEM 32, heats the water to the desired temperature. Once heated, the water is pumped to a hot water slider. A water rectifier ensures proper velocity at the slider's outlet. The slider, controlled by electromagnetic relays and a reset spring, delivers hot water into three interlayers of the brewing nozzle to achieve different brewing radii.The brewing nozzle has three outlets for different brewing radii. Hot water from the slider is delivered to the nozzle via an intricate spur gear set, ensuring precise control over the brewing process. Finally, the hot water from the brewing outlet reaches the coffee bean filter, where it brews the coffee. The brewed coffee is collected in a cup, ready to be enjoyed.

1.3.2 FSM Diagram

We are figuring out a simple way to describe the control logic of this coffee machine. [4] provided a finite state machine (FSM) paradigm that abstracts the story of how a laundry machine washes clothes well. FSMs are also abstracts for other control systems, like cooking machines [5], robots [6], and vending machines [7]. In this project, we tried to use FSM to describe our coffee machine.

As shown in Figure 3, the FSM includes the states of setup, brewing, and pumping, and set the execution order according to different input commands.

FSM Summary. Compared with the FSM in the design document, we've simplified it and made life easier. After setting the brewing method, the coffee machine tells users that how much bean powder and hot water they should add. Once the user is OK, the pumper directly pumps hot water to the 3-hole nozzle. Depending on the chosen brewing method, the machine activates a gear motor to perform a specific movement, such as a direct or rotating drop mode. If the weight sensor shows that the coffee concentration meets the set standard, the brewing cycle ends, and further water addition is stopped. If not, the process is repeated for another cycle. A more detailed explanation of FSM is provided in section 2.3.

- **Dashboard**
  - As illustrated in the figure 5, the dashboard features five buttons for user convenience and LED digital tubes to display various physical quantities such as water temperature, time, water weight, and water height.
  - The functions of the buttons are:
    - **POWER**: Turns the coffee machine on or off and can be used to shut down the machine in emergency situations such as a power short circuit, system damage, or water temperature malfunction.
    - **START**: Initiates the brewing process according to a pre-set program. It requires the type of brewing (e.g., light coffee, espresso, hot water cleaning) to be recorded before activation.
    - **LIGHT**: Selects the brewing process for light roasted coffee, simulating the method of a human hand brewing.
    - **DARK**: Chooses the brewing process for dark roasted coffee, again simulating human hand brewing.
    - **NEXT**: Once the beans and hot water are ready, the machine can work, starting from pumping water, if the user presses this button.
- **Motor Movement**
  - The nozzle utilizes a combination of straight and rotary drip methods for water dispensing, with carefully timed alternations between the two.
  - The control codes for different brewing modes are hard-coded into the circuit chip of the control system during production, as shown in another referenced figure.

1.4 High-level Requirements List

- **Precision and Consistency:** The machine should replicate the scientific pour-over skill . It should precisely control water temperature, water-bean ratio and time spent for making coffee.
- **Affordability and Accessibility:** The product should offer a more cost-effective solution than existing commercial product without sacrificing flexibility and quality.
- **Easy User Experience:** The design should be intuitive, easy to use for the specialty coffee beginner.
- **Durability and Maintenance:** The machine should be built to last, requiring minimal maintenance while operating efficiently.
- **Quality of Brew:** The coffee produced must be consistently high in quality, with taste tests confirming its superiority or equivalence to manually brewed pour-over coffee.
- **Coffee Roast Degree Difference**: The machine should be able to distinguish light roast and dark roast coffee, taking different brewing strategy on them.

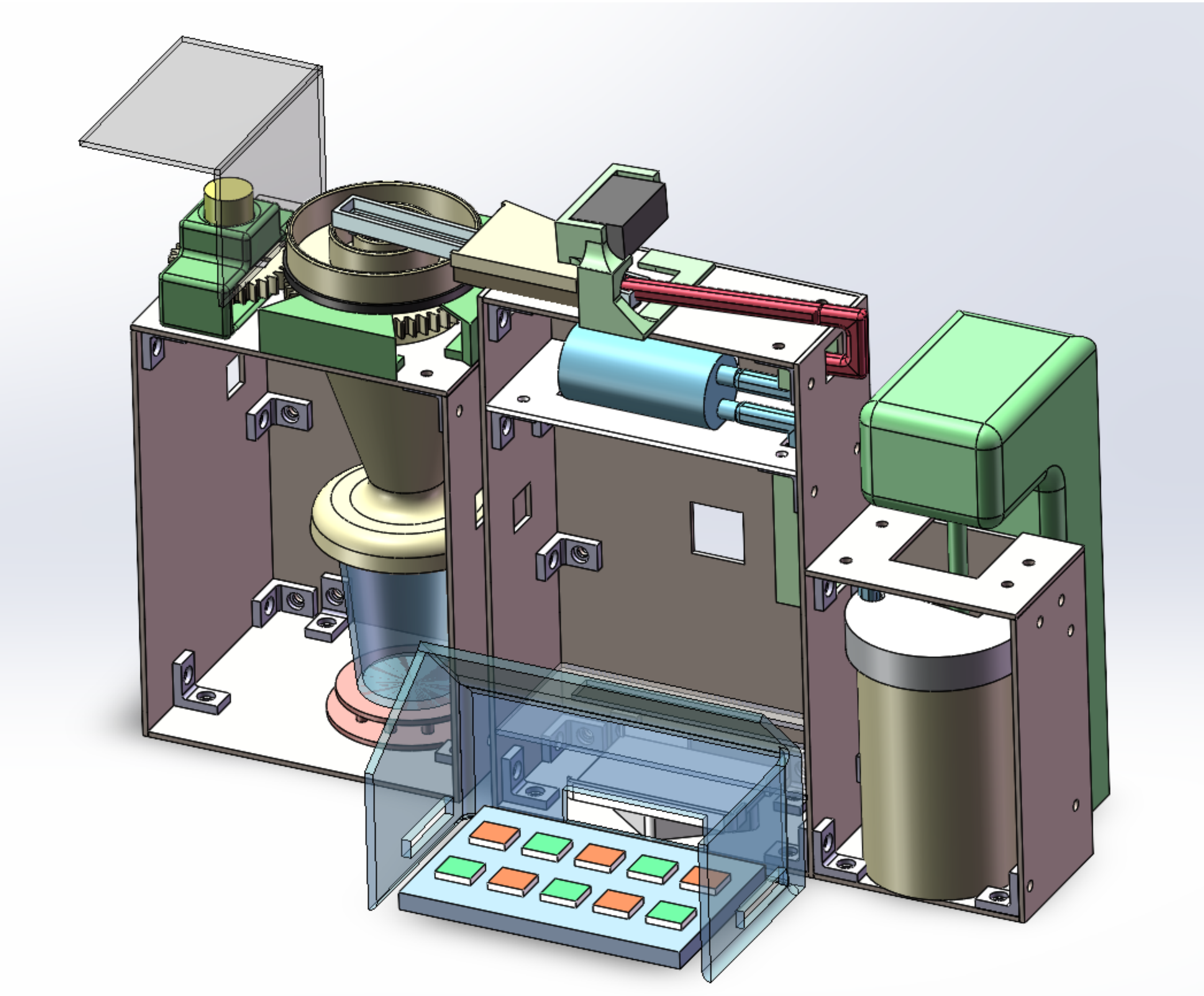

Figure 1: Latest Physical Design of Machine (Version 3, Wires are hidden)

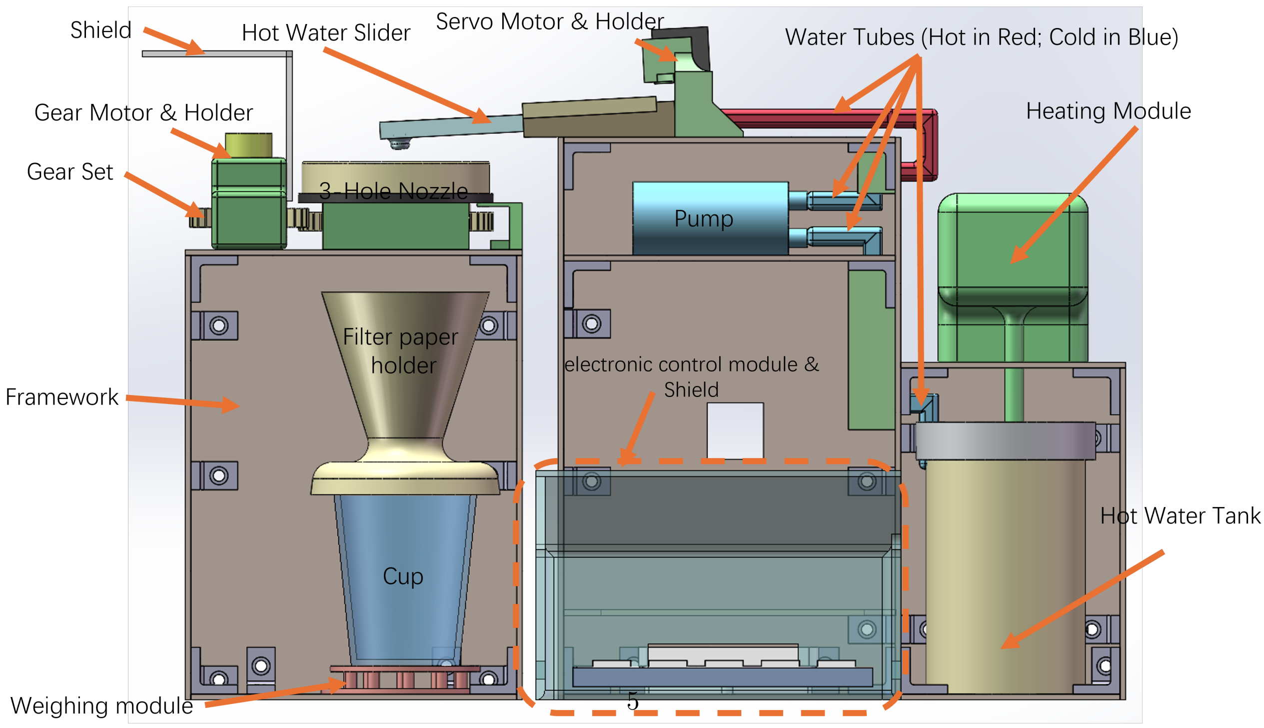

Figure 2: subsystem with names

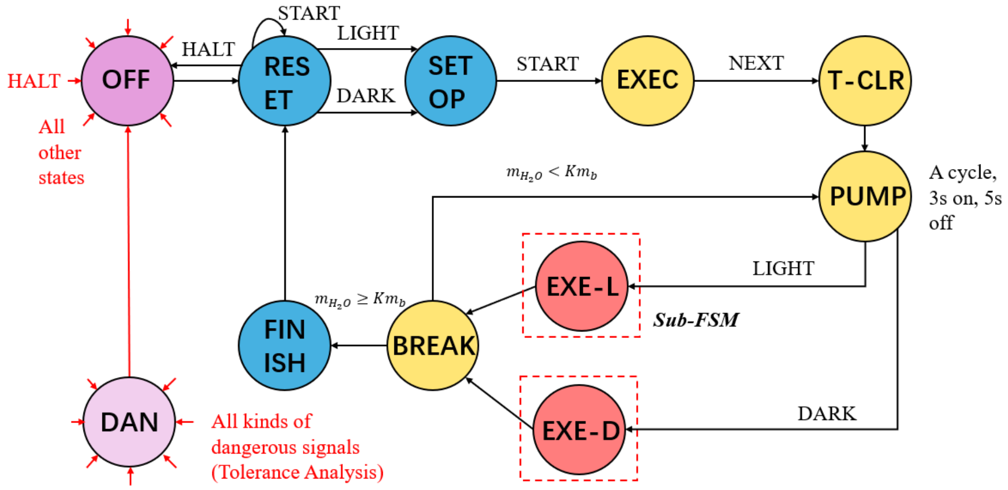

Figure 3: The finite state machine (FSM) diagram for the coffee machine. Each bubble stands for a state (what the coffee machine is doing). The arrows stand for transitions, which means the coffee machine starts to do another thing when a condition is met, or a user instruction is input. For the states' description, see Section 2.3.2. For sub-FSMs like EXE-L, EXE-D, see Figure 4 for details.

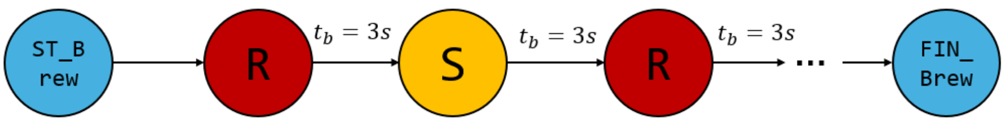

Figure 4: The figure explains how a sub-FSM (EXE-L/EXE-D) works for the dripping ways of a certain brewing type. After reaching the ST_Brew state (start brewing), the motor first drips by rotating (R), and after 3 seconds, it starts dripping straight (S) and then starts rotating and dripping again; when it reaches state FIN_Brew (finish brewing), the motor terminates.

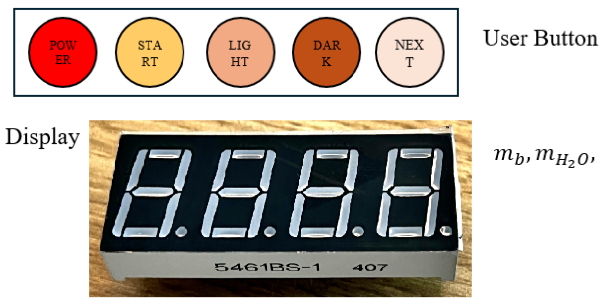

Figure 5: 4-Digit LED Display dashboard. Users can give instructions by pressing buttons. The functions of each button are explained below. The LEDs show the physical quantities (like the mass of coffee beans and water).

2 System Design

2.1 Block Diagram

Figure 6 shows the system block diagram of our design.

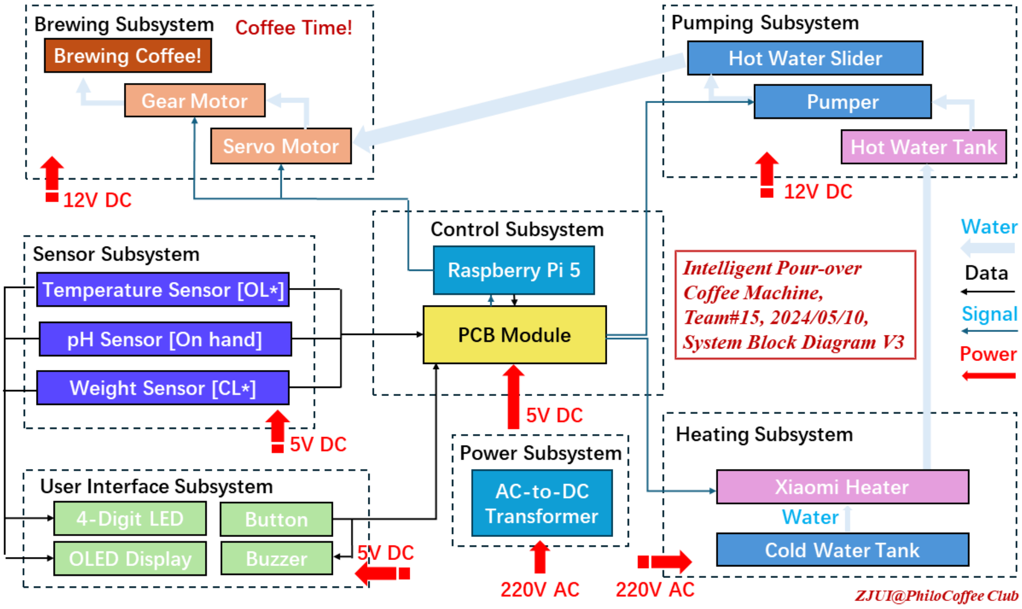

Figure 6: System architecture of our design. The power subsystem provides electricity to all other subsystems. The control subsystem acts as the human brain to supervise the operation. While the sensor subsystem provide feedback for close-loop control. The heating subsystem produces hot water to the hot water tank. The pumping subsystem transports water to the hot water slider. The user interface subsystem allows users to interact with the coffee machine. The brewing subsystem simulates a barista's hand to brew coffee. Notice OL is Open-Loop Control, CL is Closed-Loop Control. Details can view Section 3.1.

2.2 Physical Design

Table 1: summarizes all 14 components included in our coffee machine

Hot Water Tank	Heating Module	Water Pipes
Electronic Control Module (with Shield)	Pump	Servo Motor (with Holder)
Hot Water Slider	3-Hole Nozzle	Gear Motor (with Shield and Holder)
Gear Set	Framework	Weighing Module
Filter Paper Holder	Cup	

As shown in the Fig 7, our physical design consists of the following sub-systems including a coffee beam weighing system (Fig. 8), a heating module (Fig. 9), a pump (Fig. 10), a hot water slider to deliver water to the brewing subsystem (Fig. 11), and a brewing nozzle (Fig. 12) which is able to squeeze hot water out from three different outlets (Fig. 13).

Fig 8 displays a coffee beam weighing system. The weight of the coffee beam serves as the input of our system. We planned to use a piezoresistor to achieve this function. We place the piezoresistor underneath the coffee beam filter, once the user poured the coffee beam in to the filter, the piezoresistor is going to be able to generate a signal as an input to the controller, then the controller will calculate the optimum brewing condition including brewing temperature, brewing radius, waiting time and so on.In total, three different brewing radius are able to be achieved, which corresponds to three separate holes on the three-hole nozzle.

Fig 9 shows a zoomed-out view of the hot water tank (in yellow) together with a hot water generator (in green). Considering the food grade safety and operational safety, we decide to use a hot water generator from

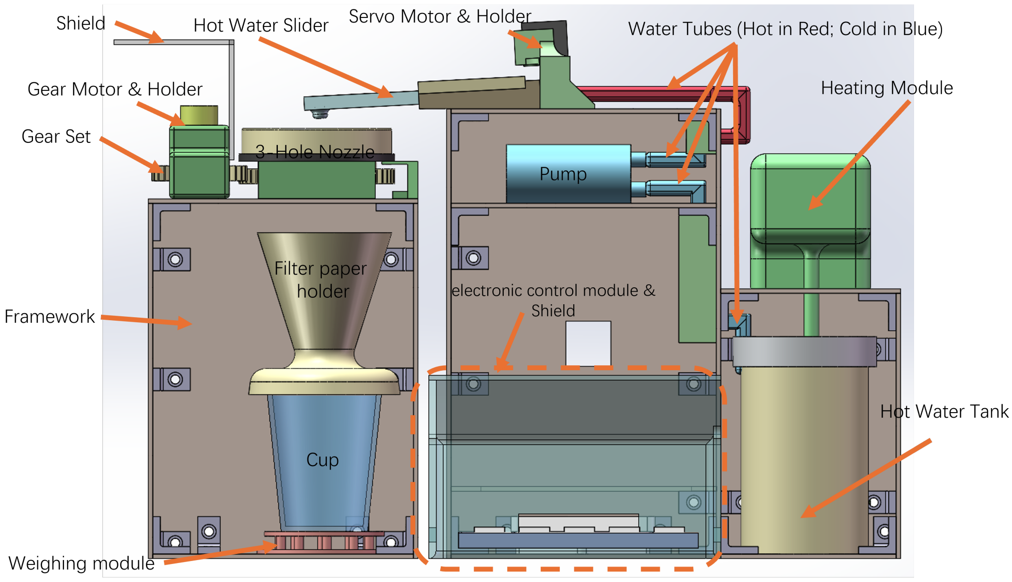

Figure 7: Subsystem Naming of the Latest Physical Design of Machine (Version 3)

Table 2: Key Parameters

Grind Size	Medium-fine grind
Coffee-to-Water Ratio	1:15
Water Temperature	Boiling (approximately 92°C)
Brewing Time	About 1 minute and 30 seconds
Raw Material	15 grams of fresh coffee beans, brewing into 225 grams of coffee

market (MSYSJ03MH Xiaomi Co.)to generate water of programmed temperature. The hot water tank is made by double-layer stainless steel with air inserted in between, air serves as a thermal insulation material due to low thermal conductivity, ensure it could sustain temperature up to boiling point of water. After the hot water tank is filled with water, a pump sucks the water into the hot water slider as shown in Fig 11. The pump is controlled using a Raspberry Pi 5 based breadboard circuit.The hot water slider is controlled by a servo motor (Black box in Fig 11), which are able to achieve adjustable and accurate rotation to deliver water to three different holes on the nozzle. It is noteworthy that the hot water slider is specially designed with a 3-degree off angle to promote the water flowing natually downward the slider. Also, the servo motor holder has the same 3-degree angle as well to fit the leaning of the slider. In our design, the hot water slider could deliver hot water into three different interlayers of the brewing nozzle to achieve three different brewing radius. The three-hole nozzle is driven by a set of spur gears, and the other spur gear is driven by a separate motor. We also designed a specially ”crossing-shaped” connection component to avoid the driving gear from slipping with the shaft of the driving motor as shown in Fig. 14

Finally, the hot water coming from the brewing outlet reaches the coffee beam filter, and after that, a cup of fragrant coffee will be there waiting for you.

2.3 Finite State Machine Design

2.3.1 Key Parameter for Brewing

Table 2 outlines the key parameters for brewing.

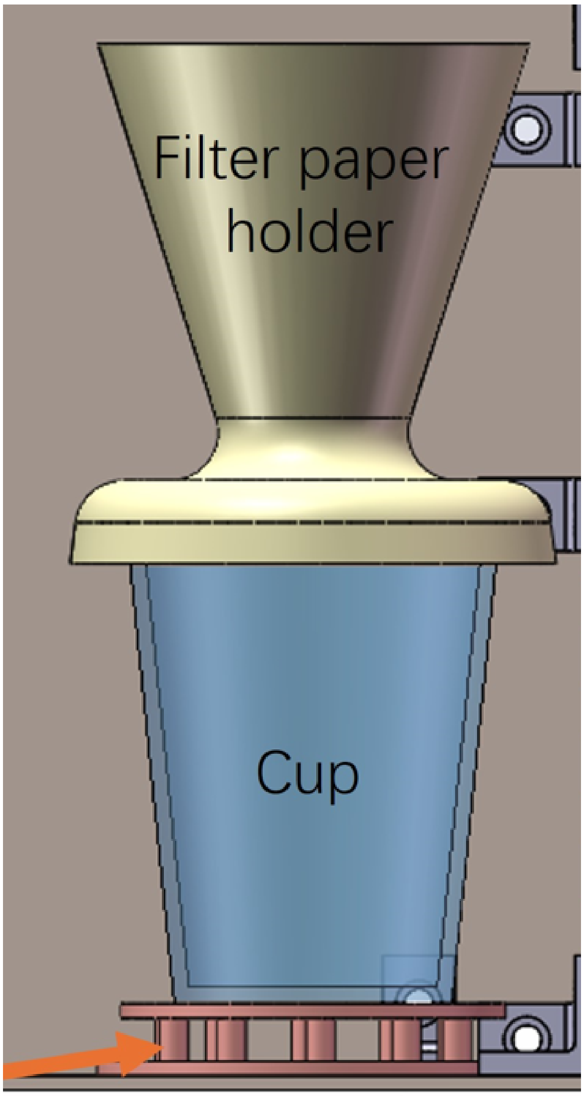

Figure 8: Weighing subsystem (in Red)

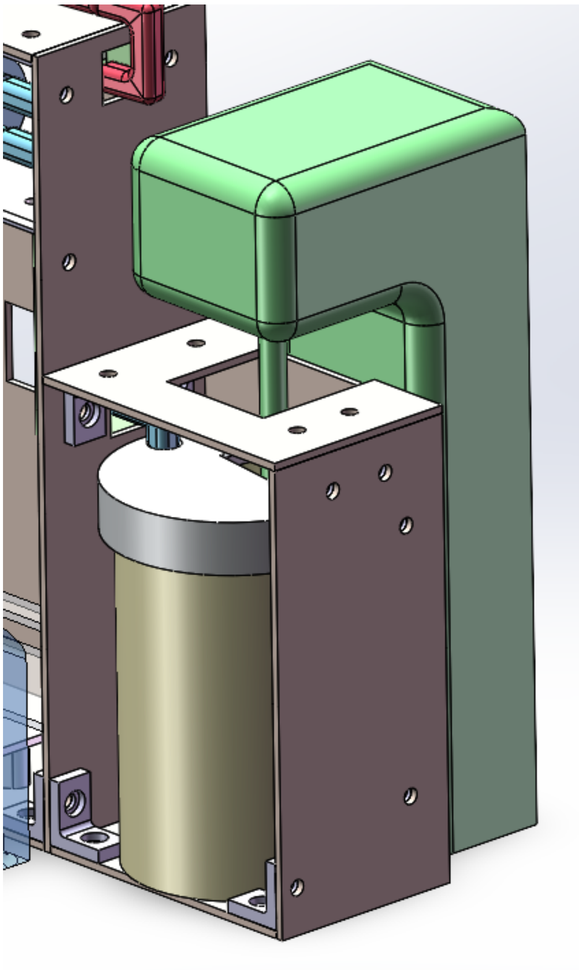

Figure 9: Heating subsystem (in Green)

Brewing Method:

1. Heat water in a kettle to 92°C and prepare the grind.
2. Pre-wet the filter and set up the brewing station with a scale.
3. Start with a 20-30 gram bloom pour, ensuring all grounds are saturated.
4. Continue with a slow pour to 100 grams, then quickly pour around the edges.
5. Finish the pour to reach a total weight of 225 grams without disturbing the flow.
6. Allow the coffee to drip through, and clean equipment with remaining hot water.

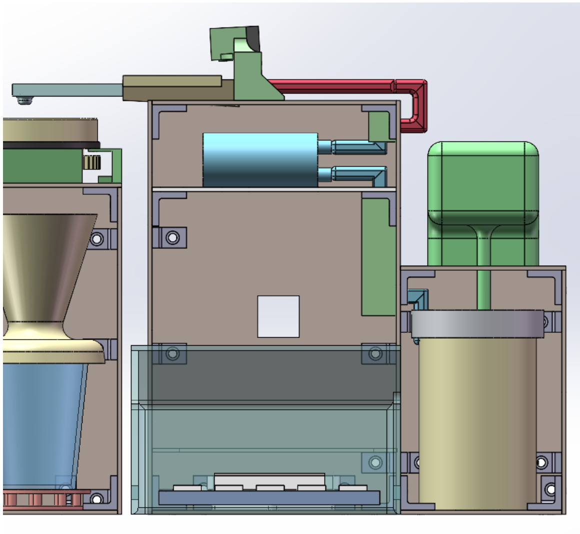

Figure 10: pumping subsystem (in Blue and red)

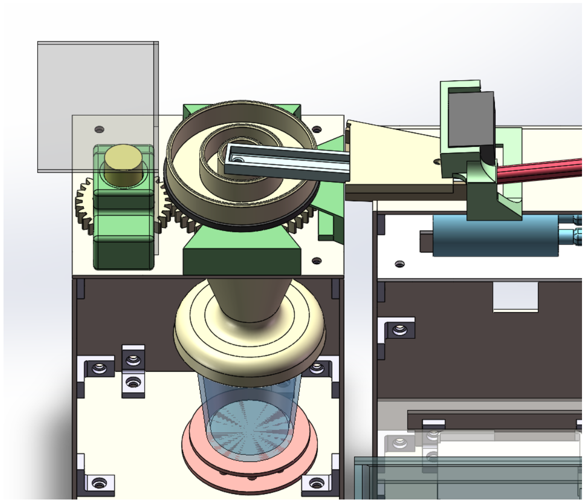

Figure 11: Brewing subsystem (in Blue and Yellow)

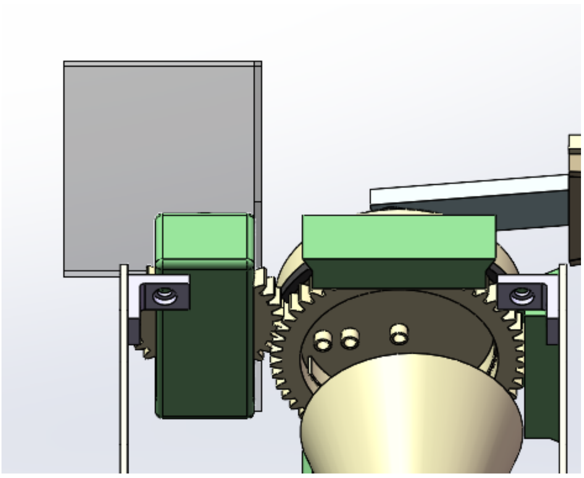

Figure 12: Three Holes of Nozzle (Bottom view)

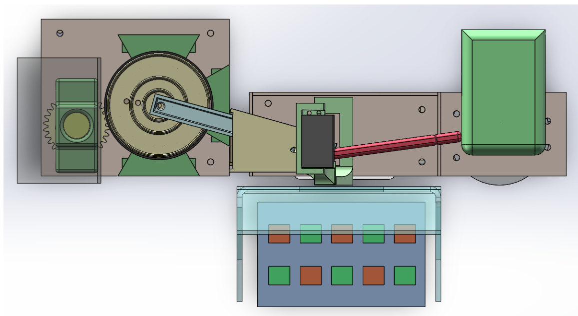

Figure 13: Three Holes of Nozzle (top view)

2.3.2 State Description

The functionality of the coffee machine is modeled using a Moore Machine with 15 distinct states, described as follows:

OFF The coffee machine is not powered on.

RESET The coffee maker is inactive and awaiting initialization.

SET-OP Sets up the operation. The coffee machine registers the brewing method selected by the user.

EXEC Executes the brewing process.

T-CLR Timer clear. Resets the timer to zero, typically to record the duration of brewing.

PUMP Pumps water to the hot water reservoir.

FLOW Channels water from the hot reservoir to the brewing nozzle via the slider.

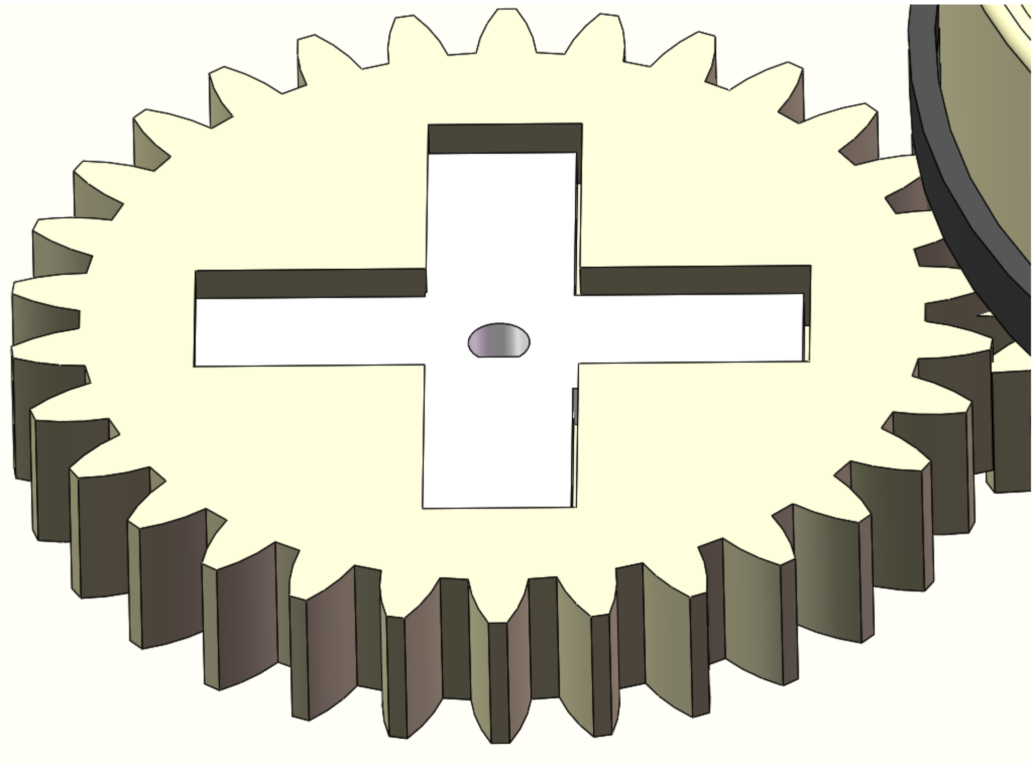

Figure 14: Special Consideration in our Design to avoid accidental slipping between driving gear and motor shaft (non-circular hole at center to connect the shaft of motor,non-circular connection between shaft and driving gear)

EXE-L/D Activates the gear motor in various modes controlled by the python code. *L/D* corresponds to light or deep roast coffee modes.

BREAK Pauses operation after a brewing cycle to allow the weighing module to assess water sufficiency.

FINISH Completes the brewing process after adequately washing the coffee beans with hot water.

DAN Indicates a hazardous situation. The machine ceases operation to ensure safety in the event of abnormal function.

2.3.3 Spatial-Temporal Diagram

Figure 15 uses a space-time chart to show the sequence of steps in the coffee machine's operation. Time points labeled t_0 to t_7 show the time progress. Each stage happens one after the other, in order. It's a simple way to explain how the coffee machine works step by step. The motor and the pumper work concurrently. The pumper pumps for a while and rest for a while. If the water is enough, stop the brewing process. The motor works according to the program we assign to it.

3 Verification

3.1 Subsystem Functions & Requirements

3.1.1 Brewing System

- **Function**: This subsystem is responsible for the physical aspects of coffee brewing, including the holding and dispensing of water and coffee grounds. It mimics the actions of a barista in a pour-over coffee-making process.

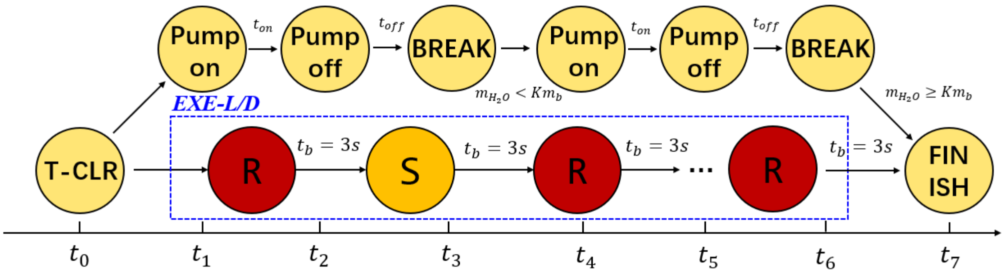

Figure 15: A spatial-temporal diagram for the brewing process. The pumper and the motor work concurrently. The upper line shows the workflow of the pumper, while the bottom line shows the workflow of the motor.

- **Requirements**:
  - Must accommodate varying amounts of coffee grounds and water.
  - Must achieve a water dispensing accuracy of +/- 5ml.
  - Compatible with standard pour-over coffee filters and holders.
- **Contribution**: Enables the physical brewing of coffee, essential for the product's core functionality.
- **Interfaces**: Receives control signals from the Control System; mechanical feedback to Sensing System.

Table 3: Verification for Brewing Subsystem

Requirement	Verification Procedure	Notes
Simulate pour-over technique accurately.	Observe and compare the technique with a standard manual pour-over.	Imitate professional barista techniques.
Allow for adjustment of brewing parameters.	Verify through UI that parameters can be adjusted and take effect.	Customization for users.

3.1.2 Powering System

- **Function**: This subsystem is responsible for the electrical power supply for the entire system, ensuring all components receive the necessary power at stable and safe voltage levels.
- **Requirements**:
  - Must convert 220V AC to a stable 12V DC output for the primary power supply.
  - Must step down 12V DC to secondary voltages of 12V, 5V, and 3.3V to power various components.
  - Integration with a custom PCB to distribute these voltages safely across the system.
  - Must include safety features such as fuses and diodes to protect against overcurrent and reverse polarity.
  - The design should include LED indicators for real-time voltage status monitoring.
- **Contribution**: Ensures reliable and consistent power delivery to all system components, which is critical for the machine's operation and safety.
- **Interfaces**: Interfaces electrically with all other subsystems requiring power, including control systems and sensors.

Table 4: Verification for Powering Subsystem

Requirement	Verification Procedure	Notes
Convert 220V AC to 12V DC.	Test with multimeter and verify stable output voltage.	Ensure compatibility with main power input standards.
Step down from 12V to secondary voltages.	Measure outputs with a multimeter; verify correct voltage levels at each output.	Check the reliability and efficiency of voltage regulators.
Safety features integration.	Perform a short-circuit test; check fuse and diode functionality.	Critical to prevent damage to electronic components.

3.1.3 Control System

- **Function**: The Control System interprets sensor data and controls the Mechanical Coffee Brewing System. It utilizes pre-trained imitation learning algorithms to replicate professional barista techniques.
- **Requirements**:
  - Must process sensor data in real time.
  - Must apply Raspberry Pi 5 for supporting the FSM and calculations.
  - Interface for receiving user input and sensor data.
- **Contribution**: Acts as the machine's brain, controlling the brewing process based on sensor inputs and helping provide a cup of delicious coffee.
- **Interfaces**: Receives data from Sensing System and User Interface; sends commands to Mechanical Coffee Brewing System.

Table 5: Verification for Control Subsystem

Requirement	Verification Procedure	Notes
Execute the brewing cycle based on user input.	Test with different user inputs and verify correct cycle execution.	Flexibility in brewing.
Respond to error conditions with safety shutdown.	Simulate error conditions (e.g., overheating) and check for shutdown.	Safety critical.
The signal should be correctly output.	Simulate the marquee experiment.	Data transmission.
The user interface buttons should work.	Simulate the button input experiment.	User interface.
The motor should work correctly, guided by the circuit.	Simulate the PWM output experiment.	Motor controlling.

3.1.4 Sensing System

- **Function**: Our design contains a lot of sensors in order to produce a cup of well-controlled and tasty pour-over coffee. Table 7. tabulated all sensor module and their functions included in the design.
- **Requirements**:
  - Temperature sensor with accuracy of +/- 1°C.

– Weight sensor with accuracy of +/- 1g.

- **Contribution**: Ensures optimal brewing conditions and provides necessary data for the Control System.
- **Interfaces**: Provides real-time data to the Control System; receives user preference data from the User Interface.

Table 6: Verification for Sensor Subsystem

Requirement	**Verification Procedure**	**Notes**
Accurately measure water temperature.	Compare readings with a standalone thermometer.	Critical for brewing quality.
Measure water temperature and weight in time.	Set a standalone timer to record the time.	Critical for brewing quality.
Detect water level in the reservoir.	Verify sensor with predefined water levels.	Prevents overflow and dry run. We can label the water level in the water tank

Table 7: All Sensor Modules and Functions in Design

Sensors	Sensor Position	Sensor Function
Weight sensor	Placed under coffee beam filter	Weigh the coffee beam weight as the input of the system for further calculation and implementation
Brewing nozzle outlet temperature sensor	At the outlet of the brewing nozzle	Give feedback of the outlet water temperature at the nozzle end

3.1.5 Heating Subsystem

- **Function**: The Heating Subsystem is tasked with heating water to the optimal temperature range for brewing coffee, typically between 85°Cand 95°C. This precise temperature control is essential for the extraction of the full flavor spectrum from the coffee grounds. The subsystem utilizes a heating element, such as a thermo-coil or a boiler, to achieve the desired water temperature.
- **Requirements**:
  - Heat water to a temperature range of 85°Cto 95°Cwithin 2 minutes.
  - Maintain temperature accuracy of +/- 2°Cduring the brewing process.
  - Implement safety features to prevent overheating and ensure user safety.
- **Contribution**: The Heating Subsystem is critical for optimizing the extraction of flavors from coffee grounds, directly influencing the quality of the brewed coffee.
- **Interfaces**: The Heating Subsystem communicates with the Pumping Subsystem to ensure water is heated before being pumped over the coffee grounds.

3.1.6 Pumping Subsystem

- **Function**: The Pumping Subsystem is engineered to transport water from the reservoir to the Heating Subsystem and subsequently onto the coffee grounds. It consists of a water pump, which may be a diaphragm or peristaltic type, chosen for its capability for precise control over the water flow rate, which is crucial for replicating the pour-over brewing technique.

Table 8: Verification for Heating Subsystem

Requirement	Verification Procedure	Notes
Heat water to 90°C within 2 minutes.	Use a thermometer to check water temperature after heating.	Essential for optimal extraction.
Maintain temperature within +/- 2°C.	Monitor temperature stability over 10 minutes of operation.	Temperature consistency is key.

Table 9: Component Specifications

Parameter	Specification	Value
Water temperature	Maximum 95°C	
Heating temperature control accuracy	±0.5°C	
Pressure	1-2 bar	
Flow rate	1-2 L/min	
Viscosity	0.89 mPa·s	
Water pump power	15-50 W	
Control system stability	Control success rate	Greater than 90%
Control system communication ability	Protocol type	PWM signal
Safety performance	Feature	Leak proof, shock proof

- **Requirements**:
  - Deliver water at a controlled flow rate of roughly 600g per minute to simulate the pour-over process.
- **Contribution**: The Pumping Subsystem plays a vital role in the automation of the pour-over coffee brewing process, ensuring consistency and precision in water delivery.
- **Interfaces**: This subsystem interfaces with the Heating Subsystem to supply water for heating and with the Control Subsystem to adjust the flow rate according to the selected brewing profile. It also interacts with the Sensing Subsystem to monitor the water level and prevent dry runs.
- **Experimental Setup and Methodology**: We systematically varied the power output to assess the pump's performance in terms of time efficiency and flow rate for dispensing 500 ml of water. The power output adjustments were made from 0% (0 degrees) to 100% (300 degrees) at specific intervals (60 degrees for 20%, 150 degrees for 50%, etc.). These adjustments were measured against the time taken and the flow rate achieved to pump 500ml of water.
- **Data Analysis and Curve Fitting**: Initial observations revealed a nonlinear relationship between the flow rate and power percentage, which suggested the inadequacy of a linear model. The following plot illustrates the relationship and the polynomial fit applied:
- **Justification for Polynomial Fitting**:
  - **Pump and System Characteristics**: The pump's performance curve, which is inherently nonlinear, stems from the mechanical design of the pump impeller and the system impedance. The impeller's efficiency varies with speed and load, altering the pump's head and flow characteristics non-proportionally.
  - **Fluid Dynamics**: As per Bernoulli's principle and the equations governing fluid motion through channels, the relationship between the pressure drop and flow rate is quadratic rather than linear. This is especially true where changes in speed lead to different flow regimes (from laminar to turbulent flow), introducing nonlinearity in the energy losses across the system.
  - **Experimental Evidence**: The collected data showed a clear pattern where increases in power did not correspond to proportional increases in flow rate, indicating the presence of factors like frictional losses and turbulence which scale nonlinearly with flow speed.

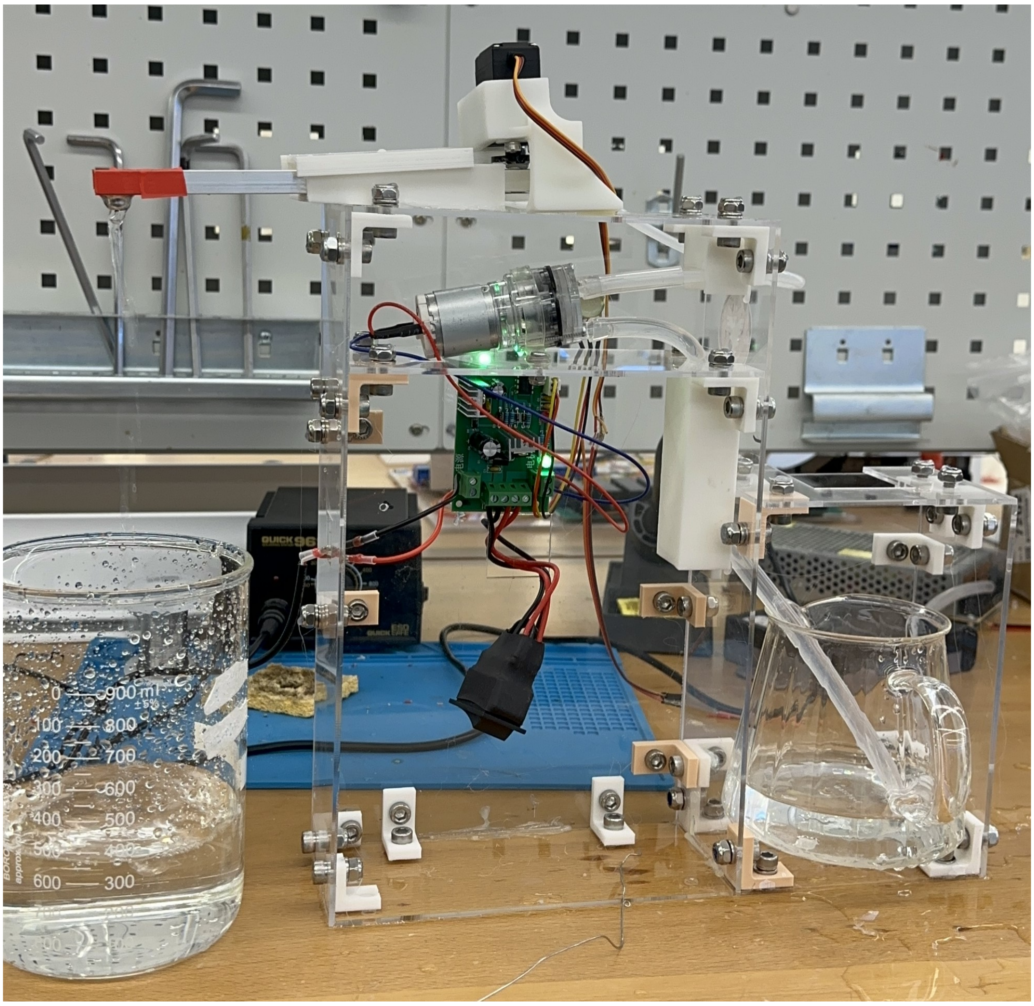

Figure 16: Initial setup of the pumping system.

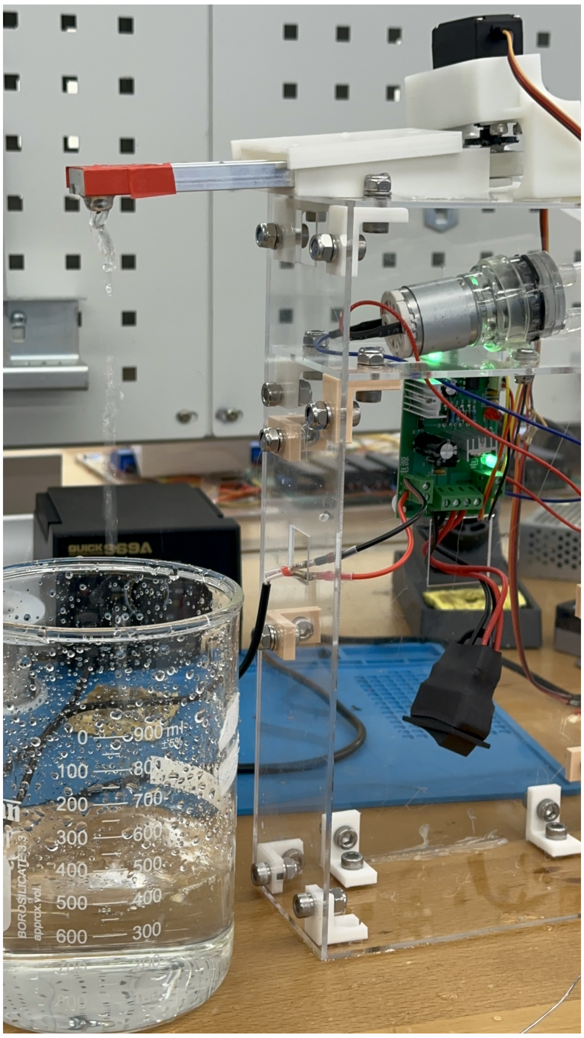

Figure 17: Pumping system during operation

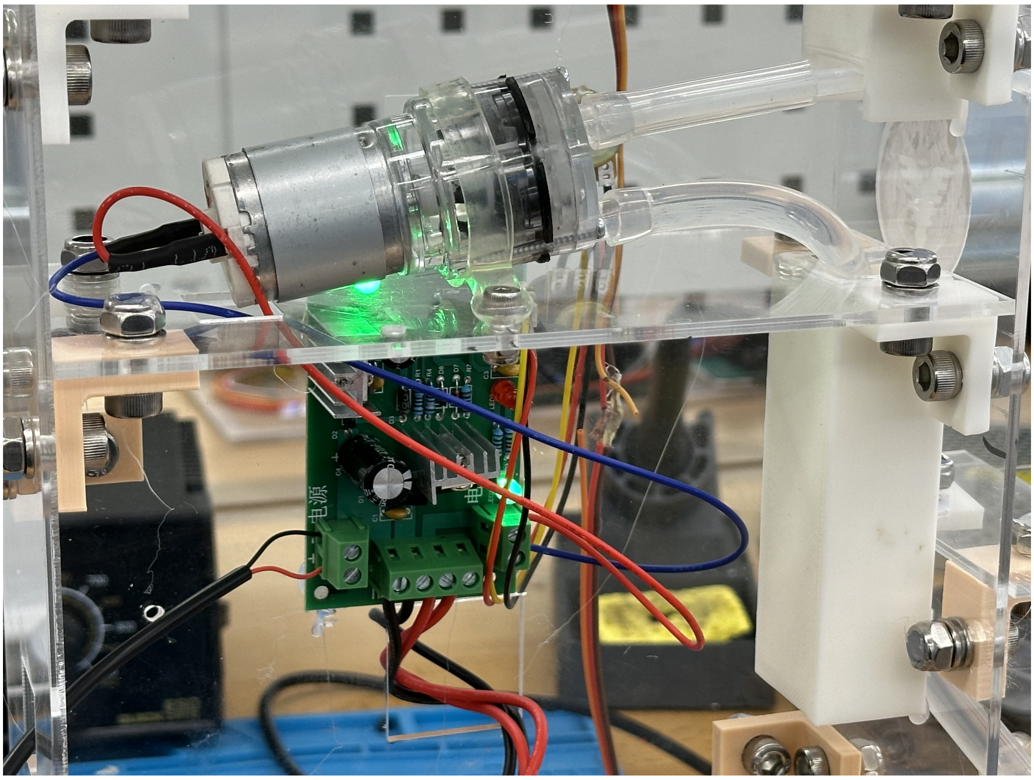

Figure 18: Close-up of the pumping mechanism.

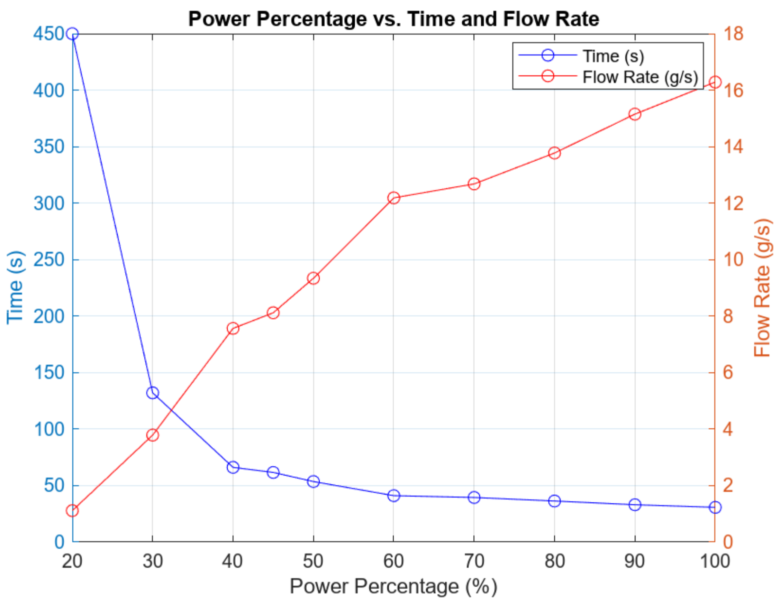

Figure 19: Power Percentage vs. Time and Flow Rate with dual y-axes

- **Results and Discussion**: The analysis confirms that a polynomial model best fits the data, accurately capturing the complex dynamics of the pumping system. This model aids in predicting the optimal operational settings to achieve desired flow rates efficiently. The optimal flow rate around 10 g/s for coffee pouring is achieved at approximately 50% power output, which aligns with industry standards for optimal coffee extraction.
- **Conclusion**: The polynomial regression model effectively captures the nonlinear behavior of the pumping

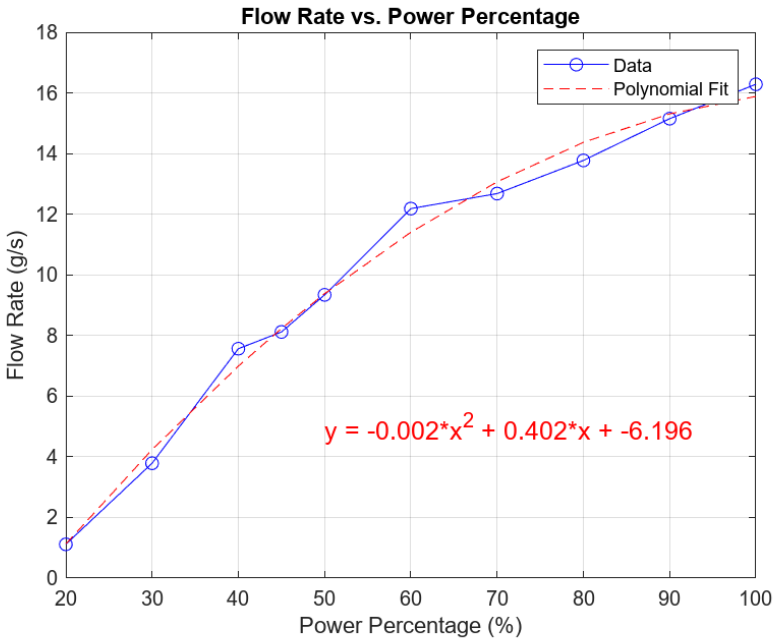

Figure 20: Polynomial fit of Flow Rate vs. Power Percentage

system under varying power settings. This approach not only facilitates a deeper understanding of the pump's operational dynamics but also supports the development of an optimized system for professional-grade coffee pouring techniques.

3.1.7 User Interface

- **Function**: This subsystem allows user interaction with the machine, enabling selection of coffee preferences and providing feedback on the brewing process.
- **Requirements**:
  - User button: intuitive, easy-to-use interface.
  - OLED is the main screen displaying brewing status and feedback.
  - The code must satisfy user journey development.
- **Contribution**: Enables user interaction and customization of the brewing process.
- **Interfaces**: Collects user input for the Control System; displays data from the Sensing System.

Table 10: Verification for User Interface

Requirement	Verification Procedure	Notes
Intuitive interface for all user interactions.	Conduct a user study with at least 10 participants to gather feedback on interface usability.	Simplify user interaction.
Display real-time brewing status.	Verify by performing a brewing cycle and observing displayed information.	Critical for user awareness.

3.2 Overall Verification

Apart from the unit test listed above, we wish to demo our machine at ***PhiloCoffee Club***, delivering a solid user feedback study to gain further improvement aspects. Inspired by Jie Wang's research experience in *Human-Computer Interaction*(HCI), we design the following user journey to verify the overall product.

User Journey for Intelligent Pour-Over Coffee Machine

As shown in figure 21, the step-by-step interaction of the user with the coffee machine, highlighting the key user inputs and machine responses throughout the coffee brewing process.

Preparing the Coffee

- **Turn on the machine**: The user initiates the brewing process by powering on the machine. This is a critical first step, requiring user interaction.
- **Select coffee type and strength via interface**: The user selects light roast or dark roast coffee, with certain cup size.
- **User grinds coffee beans with Prompt**: Prompted by the machine, the user grinds the coffee beans, adding a manual touch to the preparation.
- **User places the cup**: The user places a cup under the nozzle, preparing for the brew.

Brewing Process

- **Machine heats water to certain temperature**: automatically heats the water to the optimal temperature for the selected coffee type.
- **Machine performs pour-over**: dispenses the hot water over the coffee grounds using a controlled pour-over technique to ensure even coffee extraction.
- **User watches the brewing process**: can observe the brewing process, which is visually engaging but requires minimal interaction.

Finishing Up

- **Machine signals completion**: The machine indicates that the brewing process is complete, notifying the user through visual or auditory signals.
- **User takes the cup**: removes the freshly brewed cup of coffee.
- **User enjoys coffee**: enjoys the final product, which is the ultimate goal of the interaction.
- **User grade the coffee**: provides feedback on the coffee quality, used to adjust future brews.
- **Machine records and improves the brewing process**: records data to refine future brewing cycles, enhancing the machine's intelligence and adaptability.

Figure 21: This structured journey not only outlines the interactive process but also emphasizes the machine's intelligent features that respond to and learn from user inputs.

4 Implementation

4.1 User Study

Insights from Professional Coffee Barista

Jie Wang interviewed a series of professional coffee barista in China. Including *MAXPRESSO Coffee*(Suzhou), *Intro Coffee*(Shenzhen), *CoffeeTable&GIF*(Shenzhen) and *Starbucks*(Everywhere) etc. We focused on what is the variance in bean density and its impact on the coffee grind quality. **Specially, *MAXPRESSO* highlighted the importance of customizing the brewing process based on the grind consistency, particularly for beans with different densities**. He donated an Intelligence Pour-Over Coffee Machine to us, the ***Gemilai CRM 4106.*** Under his permission, we did inverse engineering on the machine, disassembled it and investigated the internal structure.

Smart Temperature Profiling

Questions were raised regarding the linear relationship between water temperature and the depth of the roast. This led to discussions on the necessity for the machine to intelligently adjust water temperature rather than simply following a static profile.

Criteria for Evaluation

Incorporating the Coffee Ted Lingle Flavor Wheel, we will establish an 'output criterion' for flavor evaluation. This criterion will serve as a professional and persuasive tool in assessing the machine's performance. Sources such as the SCAA flavor wheel and expert videos will be referenced to provide a comprehensive background for our flavor profiling methods [8][9].

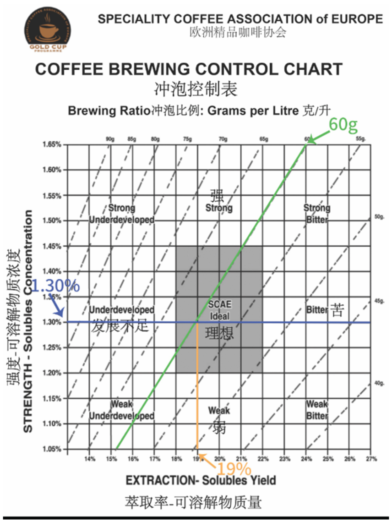

Figure 22: Chemistry Behind Coffee Brewing, this solution curve suggests how to brew the coffee with varying parameters.

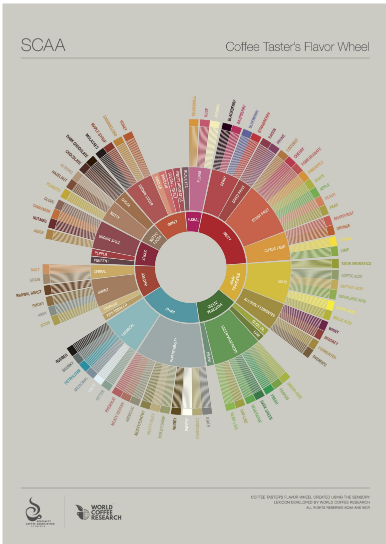

Figure 23: Ted Lingle Flavor Wheel, as highlighted by the expert barista, it is the metric for flavour certification and output evaluation.

User Interaction and Feedback

After finishing the senior design, we plan to invite the schoolmates to try our machine, providing feedback on its usability and the quality of the coffee produced. We will evaluate if the machine meets the convenience of automated systems with integrated scales. [10]. This part will strictly follow the **Ethics and Safety** section.

4.2 Reverse Engineering

Thanks @Maxspresso for supporting us with a coffee machine Gemilai CRM 4106. The inverse engineering on it really helps our design process a lot!

4.2.1 Guidance

The reverse engineering of the ***Gemilai CRM 4106*** involved detailed analyses across electronic, mechanical, and software domains to understand and document the machine's design. Encouraged by **Prof. Said Mikki, Prof. Mark Butala and Prof. Timothy Lee** , we decomposed the machine to examine the following aspects:

- **mechanical analysis** of component layout and motion mechanics;
- **circuit analysis** with component identification, power management studies, and signal flow examination;
- **software analysis** involving firmware extraction and code reversal.

The process was documented in our lab notebook, including high-resolution photos and tagged components. Safety protocols such as power disconnection and ESD precautions were strictly followed to ensure a secure working environment. This investigation not only deconstructed the physical build but also imparted insights into the design philosophy and operational mechanics, paving the way for our innovative redesigns.

Figure 24: After the machine arrives, we deconstruct the machine excitedly.

Figure 25: We check the machine from inside to outside

4.2.2 Mechanical Design

The coffee machine's mechanical design features:

- A durable filter cup and sharing pot for sustained use and quality maintenance.
- A heating base that serves both as a support during brewing and as a warmer for the sharing pot to keep coffee hot longer.
- A triple-headed rotating spray nozzle for even water distribution and efficient extraction.

Interesting Features
To address functionality and safety, the machine has some unusual components:

- The warm platform maintains the sharing pot's temperature, suitable for extended enjoyment.
- Steam venting ports prevent over-boiling and safely manage steam.
- A pumping system with a pressure relief pipe manages high-power valve operations, enhancing reliability under varying pressures.

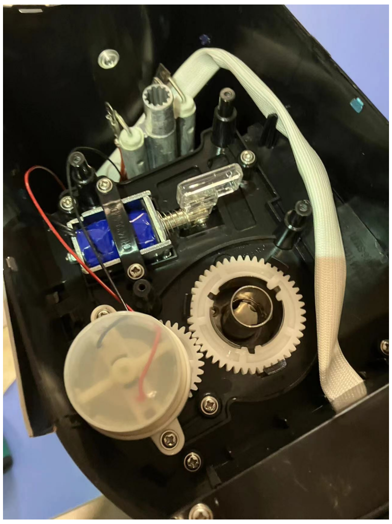

Figure 26: Brewing system featuring a hollow-pipe design to facilitate water flow through the mechanism, enhancing the brewing efficiency.

Figure 27: The DC motor with a geared head, designed for low-speed, high-torque brewing. 25 RPM, DC12V and 6W. We need to buy some similar motor.

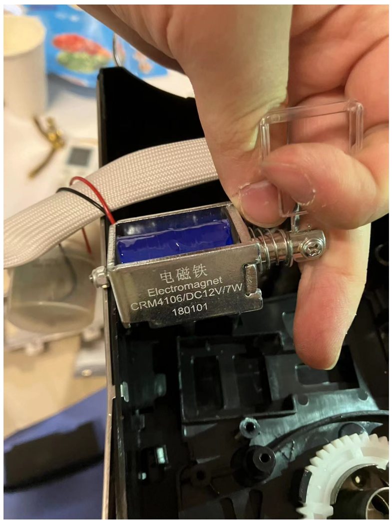

Figure 28: Electromagnet used to switch between the center and side pouring modes, illustrating the machine's flexibility in brewing techniques.

4.2.3 Electronic Design

User Interface:

As shown in figure 29, it is a User Interface (UI) circuit board equipped with buttons and LED indicators for user interaction. Below are the names and functions of the visible components on the circuit board.

1. **Buttons**

   SW1, SW2, SW3, SW4: These are the buttons on the user interface, used to initiate different operations. They appear to be tactile switches, which are small buttons that provide physical feedback and make a "click" sound when pressed.

2. **LED Indicators**

   LED1, LED2, LED3: These are Light Emitting Diodes used to indicate the status of the device. They are commonly used to display whether the device is powered on (POWER), or whether specific functions are activated, such as "1 CUP", "2 CUP", "3 CUP" for selecting the number of coffee cups, and "WATER WARM", "BLOOM", "READY" which may relate to different stages of the coffee brewing process.

   Other Components

   - **NTC**: Negative Temperature Coefficient Thermistor, used for temperature measurement. Its resistance decreases as the temperature increases.
   - **BUZ**: Buzzer, used to emit sound signals, for instance, to alert the user when the coffee is ready.
   - **CN1**: Connector, used for connecting with other circuit boards or power sources.

Powering System

Figure 31 is the circuit board of the power system. This board hosts a variety of electronic components that work together to supply power, control the power, and protect the circuit. Here are the notable components:

1. **Relays**: **RY1, RY2, RY3, RY4**: These relays are used for remotely controlling the on and off states of the circuits. Relays allow a low voltage signal to control higher power circuits and are commonly used in electromechanical systems.

2. **Transformer**: **Square component labeled "EPC25-1-4mH"**: This is a transformer used to step down or step up AC voltages.

3. **Rectifier Bridge**: **Four-legged black component, possibly marked "KB"**: This is likely a bridge rectifier, used for converting AC (Alternating Current) to DC (Direct Current).

4. **Electrolytic Capacitors**: **C1 and C2**: These cylindrical components are electrolytic capacitors, used as filters in the power circuit to reduce power noise.

5. **Thermistor**: **NTC**: This is a Negative Temperature Coefficient thermistor, typically used for circuit protection by limiting inrush current at startup.

6. **Fuses**: **F1 and F2**: These fuses are used to protect the circuit by cutting off the current in case of overload or short circuit.

7. **Filters**: **Might include gray block-shaped inductors and capacitors**: These components are used to filter out high-frequency noise on the power lines.

Designing such a power system involves considering the power requirements of the circuit, load stability, and safety protection measures. All these components work together to ensure that the coffee machine operates at the correct voltage and current and provides necessary protection in case of faults. Understanding the functionality of each component and their interrelationships is crucial for a comprehensive understanding of the entire system during reverse engineering.

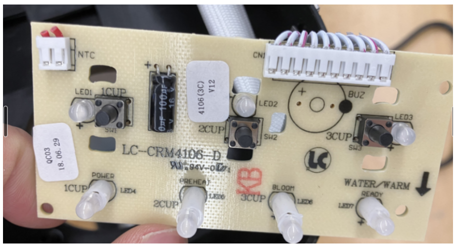

Figure 29: I/O PCB specifically designed for the coffee machine, highlighting the connection ports and components.

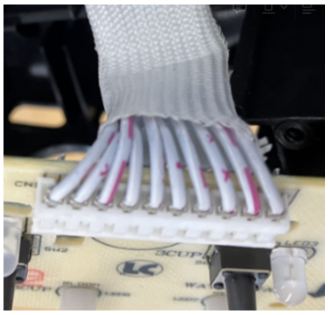

Figure 30: A flat ribbon cable. Parallel, evenly spaced wires. We can use this wire for the final product.

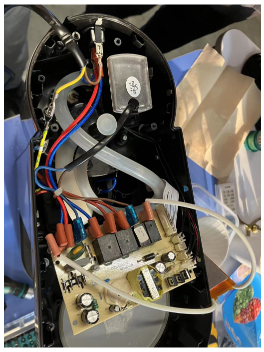

Figure 31: Detailed view of the electronic board and its connection to the pumping system.

4.2.4 PCB Design

The design of this PCB incorporates several key elements:

- **Tracing**: Copper traces on the circuit board connect all the electronic components.
- **Pads**: The areas where components such as buttons and LEDs are soldered.

- **Silkscreen**: Contains printed symbols or text that identify and describe component functions.
- **Layering**: The PCB may consist of single or multiple layers; this appears to be a single-layer board.
- **Isolation Gaps**: To prevent short circuits, there are gaps between high voltage and low voltage sections.

Designing such a PCB typically involves the following steps:

1. **Requirement Analysis**: Determine the necessary user inputs and indicator functionalities.
2. **Schematic Drawing**: Use electronic design software to create a schematic that defines the connections between components.
3. **PCB Layout**: Layout the components and traces in PCB design software based on the schematic.
4. **Check and Verification**: After design completion, perform Design Rule Check (DRC) and Electrical Rule Check (ERC).
5. **Prototype Manufacturing**: Send the design files to a PCB manufacturer to produce prototypes.
6. **Testing and Debugging**: Test and make necessary adjustments after the prototypes are made.

In practice, we consider to modify open-source PCB from platform like ***Lichuang-Open-Source***[11], making it suitable for our special mech-electric design.

4.3 Software Engineering

In this project, we manipulate the entire workflow with our software part. The software consists of Python code running on a Raspberry Pi, code packages in the electronic scale HX711 module, and the OLED display module. We explored what kind of modules could act as the core of the coffee machine. We tried the STM 32 and the Raspberry Pi 5 and found that the Raspberry Pi was a better fit for our technical stack. It was easier for us to write code on it in the easy-to-understand object-oriented design Python programming language.

4.3.1 From STM32 to Raspberry Pi 5

We started with the idea that STM32's supported programming language is C, which runs more efficiently than Python and has less risk of circuit delays. Therefore, we used STM32 as the core component in the control system.

As shown in Fig. 32, Fig. 33, Fig. 34, with the STM32, we successfully realized signal transmission (high and low levels indicated by bright and dark LEDs), time counting, and free display of OLEDs. Due to the complexity of the wiring and the frequency of poor contact conditions, we had to consider reducing the complexity of designing the wiring in-house. After four years of undergraduate study, we have become more skilled in Python than C, and the Raspberry Pi 5 supports Python programming. So, we subsequently switched to Raspberry Pi 5 as our CPU.

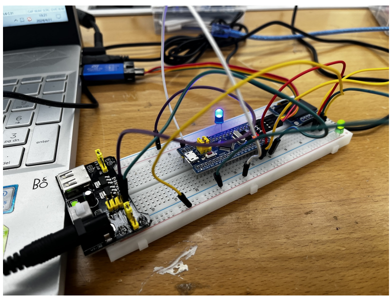

Figure 32: The signal can be successfully represented on the breadboard since the LED is lit.

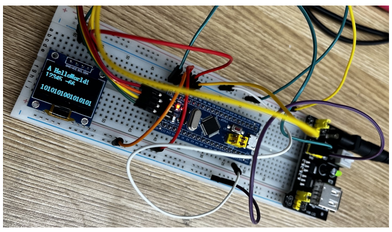

Figure 33: The OLED can display the strings by our code.

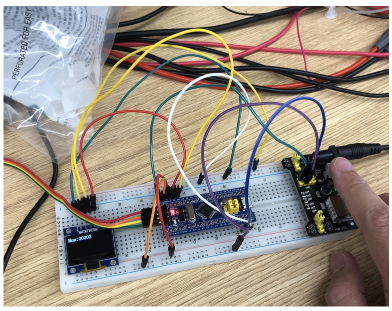

Figure 34: The OLED can display the time by our code.

4.3.2 Python Code

For this project, we built a structured Python code framework to control and manage various electronic components on the Raspberry Pi, such as sensors, buttons, LEDs, OLED screens, etc. The structured framework of our code is shown below.

```
smart_coffee_machine/
|
| main.py              # The main function, entrance of the program
|
| config.py            # The config file
|
| hardware/            # Storing hardware modules
|   | __init__.py     # Initialization
|   | button.py        # Button control and FSM
|   | display.py       # OLED display
|   | hx711_pi5.py     # Weight sensor
|   | motor.py         # Motor controller
|   | led.py           # 4 Digital LED
|   | sensor.py       # Sensor modules
|
| utilities/           # Utils, tools modules
    | __init__.py      # Initialization
    | logger.py        # Managing logs
    | timer.py         # Time calculation
```

4.3.3 Unit Tests on Raspberry Pi 5

After replacing the Raspberry Pi 5 as the CPU, the project's progress unsurprisingly became faster. The Raspberry Pi 5's support for Python programming played a key role in our project, as it fits well into our technology stack. We implemented Python code to manipulate buttons, LEDs, OLED displays, and integrated digital tube circuits.

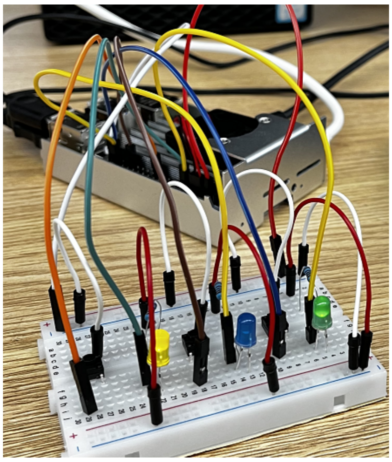

Figure 35: The button can control the LED for the signal representation.

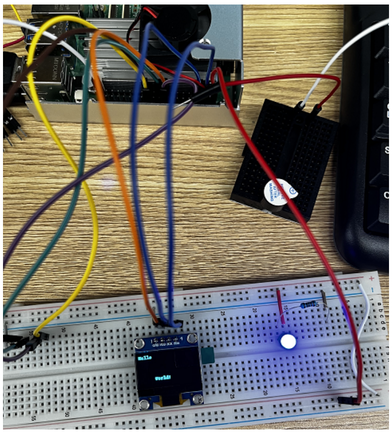

Figure 36: The OLED can display the strings by Raspberry Pi 5.

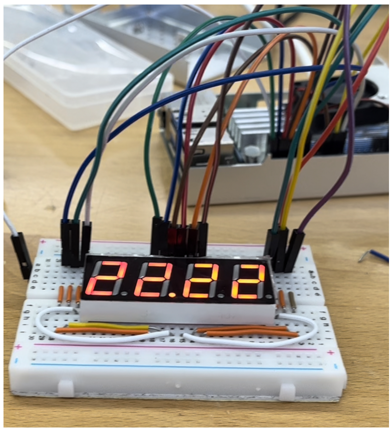

Figure 37: The digital LEDs can display the weights by our python code.

As Fig. 35 shows, The button can freely transfer the FSM from the RESET state to the SETOP state, which supports the free selection of coffee brewing mode (light roast coffee/deep roast coffee). It can also help the weight sensor to complete the tire operation or act as an emergency stop button to safeguard the coffee machine.

As Fig. 36 shows, The OLED serves as the coffee maker's main screen, guiding the user through the operation and providing feedback. The main screen displays different information when the FSM is in different states.

As Fig. 37 shows, The HX711 module acts as an electronic scale, sensing the mass of water and coffee bean powder. Through the GPIO interface, it feeds real-time data to the Raspberry Pi for state switching. The integrated digital tube displays the weighed mass, accurate to each gram.

4.4 Tolerance Analysis

- **Water Leakage:** There are multiple factors contributing to water leakage.

  1) The materials we use, which are not of industrial grade, can lead to water seeping through gaps or cracks between components.

  To determine whether it is cracking, we can utilize **Hooke's Law**:

  $$F = mg = kx$$

  and

  $$k = EA/L$$

  where F is the bouncing force, m is the water mass, g is the acceleration of gravity, x is the deformation displacement, and k is the coefficient of elasticity specified by our reservoir's materials, A is the surface, and L is the thickness of the plastic bottom, E is the Young's Module. Therefore, if the reservoir contains too much water and exceeds the force limit, it will crack and cause seeping. E of our reservoir is 1.5–3GPa [12].

  2) The presence of impurities in the water can lead to accumulation and blockages in the pipes. This can result in increased pressure, causing the components to crack or in more severe cases, even burst.

  3) Improper connections between components can cause the pump to redirect water outside the intended system inadvertently.

- **High Temperature:** To brew a delightful cup of coffee, water heated to about 90 to 100 degrees Celsius is typically required. However, certain materials used in the brewing process may not withstand this high temperature. As a result, they might partially dissolve, potentially releasing harmful substances into the water that could be toxic and even carcinogenic.

  The reservoir's material has its melt point t_{melt}. If the water temperature exceeds it, the material will melt and dissolve into the water. Therefore, we should always keep:

  $$t_{water} < 0.9 t_{melt}$$

  The thermal expansion of the reservoir should be satisfied with:

  $$\Delta L = \alpha L_0 \Delta T$$

  where α is the coefficient of thermal expansion of the reservoir, L_0 is the reservoir's height, ΔT is the change in temperature. α for polypropylene (PP) typically ranges from $6 \times 10^{-5}/K$ to $1 \times 10^{-4}/K$ at 20 °C, t_{melt} for PP is $160 - 168$°C [12]. Therefore it's safe for us to use PP for the hot reservoir.

- **Electronic Circuit Tolerance:**

- 1) For the sensor/control system and user interface, if the circuit quality or the connecting method is poor, the circuit will only work sometimes. Some of the materials will change their shape if they encounter a high-temperature environment, which will badly affect the connectivity.

  When electrical circuits deal with temperature variations, the resistance will change with respect to the temperature:

  $$R(T) = R_0[1 + \alpha(T - T_0)]$$

  where $R(T)$ is the circuit resistance with respect to the circuit temperature T, with T_0, R_0 as the factory setting temperature and resistance. We should let all the components obey this rule.

- 2) The voltage that each component shoulders is different. If the voltage is too high, the component may be destroyed. Therefore, we should carefully monitor their voltage, based on the **Ohm's law**, $V = IR$.

- 3) If there are any water leaks in those systems, the circuit will be destroyed.

- **Delay of the Sensor:** As the electronic signals travel along the wires, they encounter a series of cascade delays. This results in the machine reacting more slowly than anticipated, leading to discrepancies in the water quantity, pH value, and temperature.

  Each component can be regarded as a capacitor with capacity C, with resistance R, causing a time delay $\tau = RC$. We need to keep the time constant τ small to get faster feedback.

- **Machine Longevity:** Since this project is not intended for industrial use, the materials we've employed are of a lower quality compared to those available commercially. Consequently, if the machine is subjected to excessive use, it's likely to incur damage or potentially even break down completely.

- **Hygiene Issues:** The coffee bean grounds remain in the filter bowl after use. It's important to clean this promptly; otherwise, bacteria can proliferate, potentially damaging both the machine and the quality of the coffee.

5 Cost and Schedule

5.1 Cost Analysis

5.1.1 Introduction

The cost analysis provides a detailed breakdown of the estimated expenses required to prototype our intelligent coffee machine. This analysis takes into consideration material costs, component procurement, and potential economies of scale. Our team use Notion, a co-working software, to record all costs in detail for every team member to refer to, as shown in Figure ??. It offers transparency in the financial planning of the project and ensures we allocate our resources wisely.

Table 11: Cost Analysis for Prototype Components

Item Name	Buyer	Price (CNY)
Electronic Scale	Jingyuan	
DPS Sensor	Jie	
Max's Automatic Pour-over Coffee Machine	Jie	0
PTC Heating Sheet	Rucheng	10
DC Waterproof Heating Rod Drive Module	Rucheng	50
DC 12V Pump	Rucheng	60
Water Tank	Rucheng	20
DC Motor	Rucheng	30
Silicone Hose Flexible Water Pipe	Rucheng	15
Compression Spring	Rucheng	24
10 Meters of Flexible Hose	Rucheng	15
Heating Drive Unit	Rucheng	100
DC 12V Submersible Pump	Rucheng	85
Water Quality Detection Module	Rucheng	20
Microcontroller Motor	Rucheng	30
Single-item Metal Polishing Jig (Note: not suitable for our quality system parts)	Xubin	750

Table 11 recorded the estimated material costs of our design. We've sourced various components essential to emulate professional barista techniques. These include heating elements for temperature control, DC motors for mechanical movements, and silicone hoses for fluid transfers, among others. The cost estimates are based on current market prices and are denominated in RMB, adhering to our budget provided by ZJUI's Innovation Lab.

5.1.2 Labor and Development Costs

Table 12 summarized the labor and manufacturing cost to date included in our design. Our labor costs are computed based on the cumulative hours spent by team members in designing, programming, and assembling the coffee machine. This cost is factored in to provide a realistic estimate of the project's non-material expenses.

Table 12: Human Labor Cost Table

Description	Hours	Rate (RMB/hr)	Total (RMB)
Design and Programming	25	20	500
Assembly and Testing	25	20	500
Documentation and Reporting	15	20	300
Alluminum Alloy Component manufacturing	10	75	750
Total Labor Cost	**75h**	**-**	**2050**

5.1.3 Overall Project Cost

Table 13 shows the overall project cost, including both material cost and labor cost.

Table 13: Overall Cost Table

Cost Type	**Estimated Cost (RMB)**	**Notes**
Material Costs	215	As detailed in Cost Analysis
Labor Costs	2050	Estimated labor
Miscellaneous Expenses	300	Contingency funds
Grand Total	**2565**	**-**

5.1.4 Cost Optimization

While our current cost estimates are based on prototype quantities, we are actively seeking bulk pricing options for future scalability. Additionally, we are exploring partnerships with NGOs and corporations for possible sponsorships or bulk discounts.

5.1.5 Conclusion

The cost analysis lays the groundwork for financial accountability and helps us in maintaining cost efficiency throughout the development of our coffee machine. We will continue to monitor and update this section as we progress, ensuring we adhere to our financial plan.

Table 14: Material Cost Table

Item	Quantity	Description	Estimated Cost (RMB)	Justification of cost
Acrylic plate	10	Crafting Material for Whole Structure	0	Provided by Innovation lab ZJUI, free of charge
PTC heating sheet	2	5V, 180℃, 4-9W; 24V, 230℃, 8-20W (2*5=10)	10	-
Dc waterproof heating rod drive module	1	4A, 5V, 8W	50	-
Dc 12V pump	1	High temperature resistant	60	-
Water Tank	2	Food grade, storage for pure water, 2.52L per tank	20	(10*2=20)
DC Motor	4	9mm*2mm, 1-6V, 0.35-0.4A, 16000-20000RPM	30	-
STM32 Board	1	Basic IO, Linux System, Support Camera and Audio	128	-
Silicone hose flexible water pipe	1	10m long, inner Diameter 3mm, Outer Diameter 5 mm, Food grade, odorless, transparent, high temperature resistant	15	-
12V, 20N Push-pull Electromagnet	1	12V, 20N	30	-
Coffee Bean	N/A	Additional, Not Counted in Cost of Coffee Machine Manufacturing	0	Additional, Not Counted in Cost of Coffee Machine Manufacturing
			Total Estimated Cost	**215**

5.2 Schedule

Table 15 shows our team's schedule. We divide the tasks into 2 stage:

1. First Prototype using cold water and acrylic housing.
2. Second Prototype using hot water and 304 stainless metal housing.

Thus, we can not waste the time and get progress on the real design.

Table 15: Team Schedule

Date	Jie	Jingyuan	Xubin	Rucheng
Week 6 (3.18)	Brewing System Electronic Design	FSM Conceptual Design	Brewing System Mechanical Design	Get Designed Parts 3D Printed and Assemble the Prototype
Week 7 (3.25)	System Parameter Design & DD writing	Python Coding for FSM & DD writing	& Assemble the Printed Parts and Do Improvements &DD writing	Redesign the Pump Tube Configuration & Improve Brewing System Design & DD writing
Week 8 (4.1)	STM32 board basic IO deployment	PCB Design and Code Loading (Brewing System, Heating System)	Assemble the Plastic prototype with Rucheng & Improve the Design to Next Generation	Dictate Aluminum Alloy Manufacture & Assemble the Prototype with Xubin & Seek Potential Improvement of Prototype
Week 9 (4.8)	First Prototype Assembly	PCB Design and Code Loading (Control System, Pumping System)	Design PCB Circuit with Jie	Optimize the Control System and Design better codes with Jingyuan
Week 10 (4.15)	Overall Electronic Design Enhancement	Start implementation & Debug	Prototype and Final Product Manufacturing with Rucheng	Prototype and Final Product Manufacturing with Xubin
Week 11 (4.22)	Second Edition Assembly	Continue implementation & Debug	Back up Flexible Time	Back up Flexible Time
Week 12 (4.29)	Back up Flexible Time	Design optimization	Back up Flexible Time	Back up Flexible Time
Week 13 (5.6)	Back up Flexible Time	Design optimization	Back up Flexible Time	Back up Flexible Time
Week 14 (5.13)	Begin final report.	Begin final report.	Begin final report.	Begin final report.
Week 15 (5.20)	Continue on final report.	Continue on final report.	Continue on final report.	Continue on final report.

6 Conclusions

6.1 Accomplishment

We implmented 80% of our previous design document...

6.2 Uncertainties

During the difficult development, we made many sad decisions, such as...

6.3 Ethics and Safety Consideration

Aligning with IEEE and ACM ethical standards[13], we adheres safety regulations during the whole project.

6.3.1 Ethics Factors

1. **Assess Impact on Society:** This project is ethically right to the society, to date cultivating a coffee masters normally requires more than 1000 hrs at least, and also needs consistent training to keep their skills. Our intelligent coffee machine could offer those living in rural or leading a poor life who also want to try well-brewed pour-over coffee a chance to live with high-quality coffee. In all, the coffee machine is designed to enhance the quality of life while minimizing waste and negative impacts.

2. **Fairness and Non-discrimination:** The intelligent pour-over coffee machine will be accessible and usable by a wide range of individuals, ensuring that there are no biases in design or operation based on race, gender, or other personal characteristics.

3. **Honesty and Transparency:** The development process will be conducted with honesty and transparency. Capabilities and limitations of the coffee machine will be communicated clearly, along with safety features, maintenance needs, and any potential risks.

6.3.2 Safety Factors

1. **Burn Prevention:** To prevent injuries such as severe burns from hot coffee spillage, the machine includes safety features like the emergent button to control the temperature and prevent accidental spillage [14]. Also, we need to take care of the heat. This requires meticulous material to ensure that components can sustain with high temperatures. The hot water pump tube, hot water slider, and hot water reservoir in our design, are effectively insulated. Further, the we need clear warning label and careful user guide to reduce the risk of burns. Moreover, our control system will take temperature regulation mechanisms to prevent overheating incidents, safeguarding users during long time usage.

2. **Pathogen Transmission:** The machine will be designed for easy cleaning to avoid becoming a breeding ground for pathogens, ensuring compliance with hygiene standards in healthcare and food safety regulations [15].The mitigation of pathogen transmission risks constitutes a crucial ethical consideration in the development of the coffee machine. Central to this endeavor is the selection of materials resistant to microbial proliferation and conducive to ease of cleaning. In our design, we choose to apply Aluminum alloy as one of the food-safe materials to components that have potential to be in intimate contact with running water and coffee beam. Furthermore, adherence to stringent hygiene protocols throughout the product's lifecycle is imperative to minimize contamination risks. Attention must also be directed towards ensuring the quality of water used in the machine, adhering to established standards to prevent the transmission of waterborne pathogens. In our design, we try to round all inside edges off, to avoid straight angles which might increase the difficulty for cleaning after operation. By prioritizing these measures, the coffee machine can uphold robust sanitation standards and promote user well-being.

3. **Mechanical and Pressure Safety:** The machine will adhere to the ***Pressure Systems Safety Regulations (PSSR)*** with regular inspections, safety checks, and emergency shutoffs to prevent system failures [16].The part that are related to pressure issues include only the cold and hot water pumps, we solve this concerning by adding two pressure and temperature sensors to them respectively. The assurance of mechanical and pressure safety features within the coffee machine design and manufacturing processes

is integral to mitigating risks of accidents and injuries. Rigorous structural analysis and testing are indispensable to ascertain the machine's capacity to withstand operational stresses and pressures. Additionally, After the whole brewing process is accomplished, how to release the remaining pressure inside the water tube is also well-considered and addressed through adding gas-release and liquid release step at the end of programming, since over-pressure scenarios could compromise mechanical integrity. By adhering to these principles, the coffee machine can engender user confidence in its reliability and safety.

4. **Electrical Safety:** The electrical components of the machine, including the motor and circuit control, are designed with rigorous adherence to electrical safety standards to prevent any risks of electric shock, short-circuiting, or fire. The machine's design includes proper grounding, insulation, and overcurrent protection features to ensure safe operation. Components that may come into contact with water are waterproofed or appropriately sealed. Furthermore, we incorporate fail-safe mechanisms and redundant circuits to provide an additional layer of safety in the event of component failure. These precautions help to safeguard against the potential dangers that can arise from the machine's electrical systems. To ensure comprehensive protection, all electrical design and components will comply with the ***International Electrotechnical Commission (IEC) standards*** for household appliances. Regular electrical safety assessments will be conducted throughout the development process. By implementing these safety measures, we aim to protect not only the users but also any maintenance personnel who might interact with the machine's electrical systems.

In the Innovation LabD221, our team allows follow the safety and ethical requirements, protecting ourselves and the potential users in the future.

6.4 Future Work

In the future, we aim to further enhance the capabilities and efficiency of the Intelligent Pour-Over Coffee Machine. We have several key areas targeted for development:

- Implement a complete, closed-loop hot water system. Currently, the method to prompt the user to heat water is primitive; we plan to automate this process to streamline operations and enhance user experience.
- Integrate Large Language Models (LLMs) as agents to enable more intelligent analysis of brewing experiences and techniques. This integration aims to leverage advanced AI to refine and optimize the brewing process based on accumulated data and learning algorithms.
- Develop a more comprehensive power system by integrating the entire system into a single PCB. This will facilitate easier wiring and enhance safety by minimizing exposed components and connections.

These advancements will focus on improving not only the technical aspects of the machine but also the practical usability and safety features, pushing the boundaries of automated coffee brewing technology.

6.5 Summary

All in all, it is an interesting senior design with both innovation and commercial potential. We will work hard on it and deliver a good end for our graduation at ***ZJU-UIUC Institute***!

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