Automated Specialized Coffee Machine

By

Brandon Eubanks

Justin Yang

Sachin Parsa

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TA: Channing Philbrick

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Abstract

Coffee is one of the largest industries in the world, it is commonly said that the consumption of coffee in a culture comes in “waves”, with each wave comes a different way for coffee to be consumed. The United States is said to be in the “third wave” of coffee drinking, in which coffee is generally seen as an artisanal beverage. One potential issue with third wave coffee is that, while it is lauded for its superior flavor characteristics, it is generally much more labor intensive to prepare. This is where the Automated Specialized Coffee Machine comes in handy. In this project, we aim to make a product that can automate the coffee making process for an AeroPress coffee allowing the user to make higher quality coffee with minimal effort.

Contents

1. Introduction

The coffee industry is one of the biggest industries in the United States. The retail value of the U.S. coffee market is estimated at $48 billion dollars with specialty coffee comprising approximately 55% share by cost [1]. Specialty coffee sales are increasing at an impressive rate of 20% per year. Coffee statistics show the average consumption per individual is 3.1 cups of coffee per day in the United States [2]. The popularity of specialty coffee has increased rapidly in recent years, with 59% of cups of coffee consumed in the U.S. being specialty coffees versus 41% non-specialty [3]. These statistics suggest that American people are being more and more obsessed with drinking specialty coffee. The main problem faced with the adoption of specialty coffees is that the process of making specialized coffee like French press or AeroPress takes a lot of time, effort, and precision. After some market research, our team determined that, there are no automated specialized coffee machines in the market targeted for consumer or coffee shop use. We propose to automate the process of making a cup of AeroPress coffee, which would save individuals time and effort in preparing high-quality coffee every morning.

The final product must be able perform the following high-level project functionality:

- The coffee machine must brew and dispense one cup of AeroPress coffee at a time.
- The kettle temperature must be programmable between 175 °F – 210 °F in 5 °F increments.
- The pressure used will be 0.55 bar for pressing the coffee beans and it must be consistent within a range of ± 0.2 bar.

The process of making an AeroPress coffee involves heating the water to a temperature between 175 °F – 210 °F and applying a pressure within the range of 0.35 bar to 0.75 bar. The high-level project functionalities are made to ensure we meet these parameters, and determines the success of this project.

1.1 Functional Overview

The process of making a cup of AeroPress coffee can be broken down into three primary functions: grinding the coffee beans, heating the water, and extracting the hot water. Ground coffee is reasonably priced even compared to whole beans, and is highly available, so the focus of this project is on heating the water, moving the ground beans into the press, and applying pressure to perform the hot water extraction.

In this project, we used an AeroPress for hot water extraction. The water is heated in a kettle and gravity-fed into the AeroPress. A solenoid will open/close a valve, allowing water to be delivered to the press. A bidirectional actuator is used to apply pressure to the AeroPress for the extraction of coffee. In a similar fashion, a feed motor is used to gravity-feed coffee grounds into the press using a feed motor. Prior to the hot water extraction, the water is heated to a user-defined temperature. The temperature is monitored with a temperature sensor and used to control the kettle; based on the temperature, the power for the kettle is turned on or off.

Due to the cost issues and complexity associated with having a custom IC fabricated, a microcontroller (ATmega328p) is used to read input from the switches and sensors. The microcontroller uses this information to perform the control flow, using relay modules [4]. The microcontroller controls the power to the actuator and electric kettle accordingly; the system progresses through various stages of the coffee making process.

1.2 Subsystem Overview

The Automated Specialized Coffee Machine consists of three main subsystems: the grounds subsystem, the water subsystem, and the press subsystem. The functionality of these three subsystems are described in more detail individually.

1.2.1 Grounds Subsystem

The grounds subsystem serves to deliver the coffee grounds into the AeroPress. The grounds are placed into a reservoir, and a feed motor is at the bottom of the reservoir. This motor is controlled electronically by the microcontroller using pulse-width modulation (PWM) signals. Once the microcontroller sends a signal to the feed motor, the grounds pass through the feed motor into a copper pipe with a 120 degree slope that feeds into the AeroPress.

1.2.2 Water Heating Subsystem

The water subsystem has two main functionalities: heating the water and transferring water into the AeroPress. For the process of heating the water, power is supplied to the kettle from the wall through the use of a relay module, which in turn is controlled by the ATmega328 microcontroller. The kettle continues to heat the water, until the user-defined temperature is reached. Throughout the process, the water temperature is monitored by a simple temperature sensor, which communicates with the microcontroller. After the water reaches desired temperature threshold, a solenoid valve opens and the water is allowed to pass into the AeroPress.

1.2.3 Press Subsystem

After the water and the coffee grounds have been combined inside the AeroPress chamber, the plunger needs to be pushed downward for the coffee to be dispensed. An actuator of 60 lbf is used to push the plunger of the AeroPress. The microcontroller manages this process: the actuator continues to move forward in tiny increments until the internal limit switches are triggered. This process pushes the water through the filter and into the coffee cup, dispensing a cup of AeroPress coffee.

1.2.4 Power Subsystem

The power subsystem serves to supply power to all the other subsystems. This subsystem consists of a 12 volt AC/DC adapter; a 5 volt AC/DC adapter; and a relay, which controls the power being supplied to the power for the kettle in the water heating subsystem.

1.2.5 Control Subsystem

The control subsystem takes sensor input from all other subsystems and uses this information to control the process flow. For instance, the control system takes temperature readings from the temperature sensor and uses these readings to determine whether or not the kettle should be switched off.

1.2.6 Block Diagram

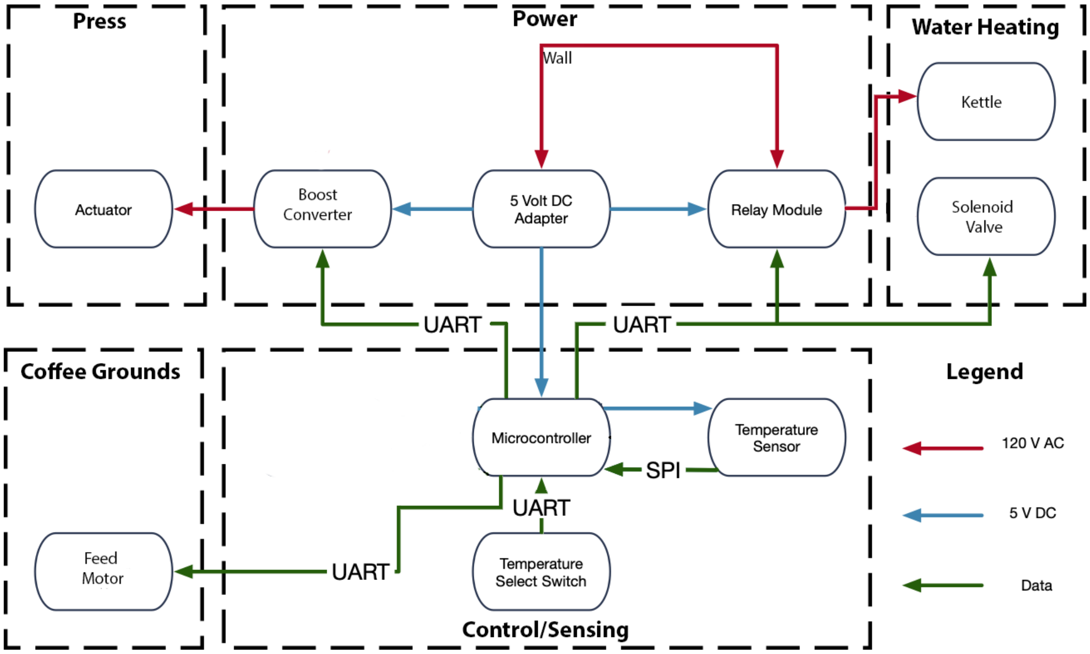

Fig. 1: Block diagram for the automated coffee machine.

2 Design

2.1 Design Process

2.1.1 Water Heating Subsystem

2.1.1.1 Solenoid Valve

Whilst designing the Automated Specialized Coffee Machine, the one major concern was the toxicity of the constituent parts. Since the goal of the project is to produce a cup of coffee, the coffee is intended to be consumed by the user. This limitation manifested itself in the form of carefully choosing which materials could be used for the water subsystem. For instance, no alloys of copper (e.g., brass, bronze) or chromium (e.g., stainless steel) could be safely used due to the toxicity of these metals. The grounds subsystem was largely unaffected by this concern since the diffusion coefficients of these metals at room temperature are very low, and, as a result, it is highly unlikely that concerning levels of toxic metals will adhere to the grounds. The water subsystem, however, was directly affected. This constraint greatly limited the choices in solenoid valves that did not use the aforementioned alloys. Budget constraints further limited the options to a 12 volt DC aluminum solenoid valve: part JWDCF2V025-06.

2.1.1.2 Temperature Sensor

Temperature selection is a crucial component of making coffee. The temperature of the water directly impacts how fast the coffee is extracted from the grounds into the liquid, which is important to the user in terms of taste. The overall target is to create a system that allows users to select their temperatures within 5 degree Fahrenheit increments. As previously mentioned, the kettle stops heating the water once the desired temperature is reached. This control mechanism means that the temperature sensor for the project needs to be accurate within 5 degrees Fahrenheit. That being said, precise digital temperature sensors are widely available to precisions within sub-degree increments, so the concern ends up being mostly around choosing a waterproof temperature sensor since the temperature sensor would be placed inside hot water. These design concerns lead to the selection of the waterproof Sparkfun DS18B20 for the project's temperature sensor.

2.1.2 Grounds Subsystem

2.1.2.1 Feed Motor

The grounds subsystem went through a series of changes throughout the design process, which are detailed further in the design alteration section of this report. The final iteration of the grounds system utilize a feed motor, which was controlled by the microcontroller through pulse-width modulation (PWM). This part was selected, in part, due to its availability and shape.

2.1.2.2 Piping Contact Angle

One other design aspect of the grounds system is the angle of the piping. It was empirically determined that a 120 degree slope would allow most of the coffee grounds to pass through the piping. 120 degrees was chosen as it is a common angle for PVC pipe, making for cheap and simple testing prior to the final construction of the device.

2.1.3 Press Subsystem

2.1.3.1 Actuator

When selecting an actuator, it is imperative that a model is selected that is able to apply enough force to the plunger to force the water through the grounds and filter. To find out the amount of force required for this use, typical AeroPress internal pressures were referenced to back-calculate the amount of force applied based on the cross-sectional area of the AeroPress plunger, which is further detailed in section 2.3.2. Measurements of the AeroPress press pot are also taken to determine the stroke length required to press the plunger fully into the press pot. These measurements lead to the selection of a 12 volt DC, 60 lbf 4-inch stroke actuator: part S100-100-12-15.

2.1.3.2 Motor Drive Circuit

As mentioned previously, both the solenoid valve and the actuator are 12 volt DC motors. These choices were design issues as the ATmega328P will only output up to 5 volts. In particular, if 5 volts are passed into the gate of an NMOS transistor, the source of that NMOS can only be pulled up to a maximum of 5 volts. This limitation is because at $V_S = 5\,V$, $V_{GS} = 0\,V$, at which point the transistor will turn off, preventing any additional current from passing through to charge the capacitance at the source terminal. It is assumed that leakage current is negligible. If instead the gate voltage is pulled up to 12 volts, the source terminal can be raised to a higher voltage, although, due to body bias effects, NMOS cannot pass a "strong" high voltage, meaning the source still cannot be pulled up to 12 volts. This configuration allows more voltage to be placed across the terminals of an actuator. The LT1613CS5#TRMPBF was chosen to do the DC voltage step-up based on these factors.

2.1.4 Power Subsystem

The primary concern of the power subsystem is that it needed to be able to safely supply enough power to the other subsystems. The kettle in the water subsystem is especially concerning as it draws the most power. The Aicok Electric Gooseneck Kettle draws 1000 W of power. Assuming 120 V AC of voltage, this connection yields an AC current of less than 10 A. These calculations made the NewZoll B01N3LGV7J a good fit for the job as it is rated for 10 amps at 120 volts.

2.1.5 Control Subsystem

The control subsystem consists of the microcontroller. When it came to selecting the microcontroller, the ATmega328P was chosen for its prototyping capabilities as Arduino Uno boards are readily available, as well as familiarity amongst the team with this specific microcontroller. Additionally, there is a wide hobbyist community around Arduino, which made it a good choice for support in case issues occur during development.

2.2 Design Alternatives

2.2.1 Physical Design

The mechanical design of the Automated Specialized Coffee went through many iterations before it was finalized. Initially the plunger was intended to come completely out of the press pot, and the grounds and the water would be fed in from the top. Eventually it was realized that this caused a clearance issue with the plunger. From here it was decided that the piping should come into the side of the press pot through holes drilled into the sides, thus resolving the clearance issues. Figures 3, 4, and 5 below show the physical specifications.

2.2.2 Grounds Subsystem

The grounds subsystem is another aspect that underwent several changes. Initially it was thought that the product would grind whole beans and pass them onto the AeroPress. It was decided that adding and controlling a burr grinder, which is required for consistent grinds would be too expensive as burr grinders are upwards of $150. Then after resolving the clearance issue an auger was considered to push the grounds into the AeroPress. This component was determined to be too mechanically complex, and there were concerns about the additional unneeded complexity. As a result, a gravity fed method was used instead. Originally, the grounds would be gravity fed into a solenoid similar to the water system, however, a feed motor was selected due to availability of parts for prototyping.

2.3 Diagrams and Schematics

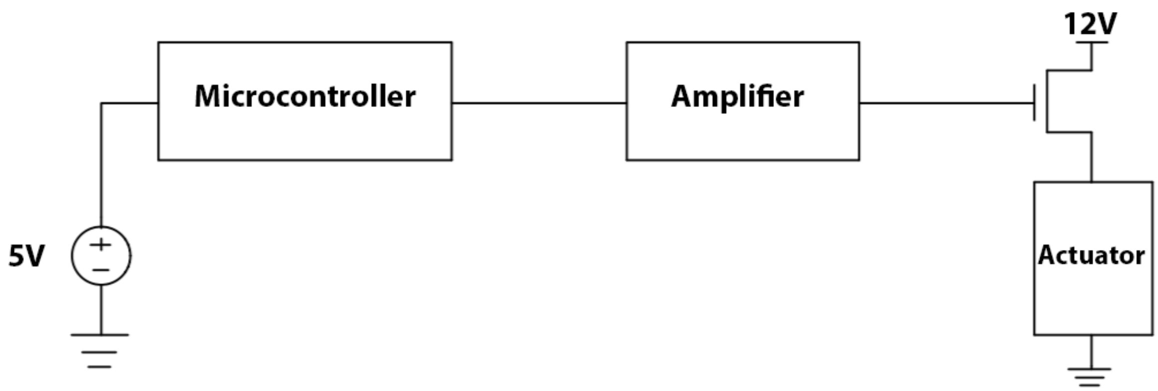

Fig. 2. Basic circuit diagram showing the actuator driver circuit. The UART output of the microcontroller is amplified and sent the the gate of a power MOSFET.

2.3.2 Circuit Schematics

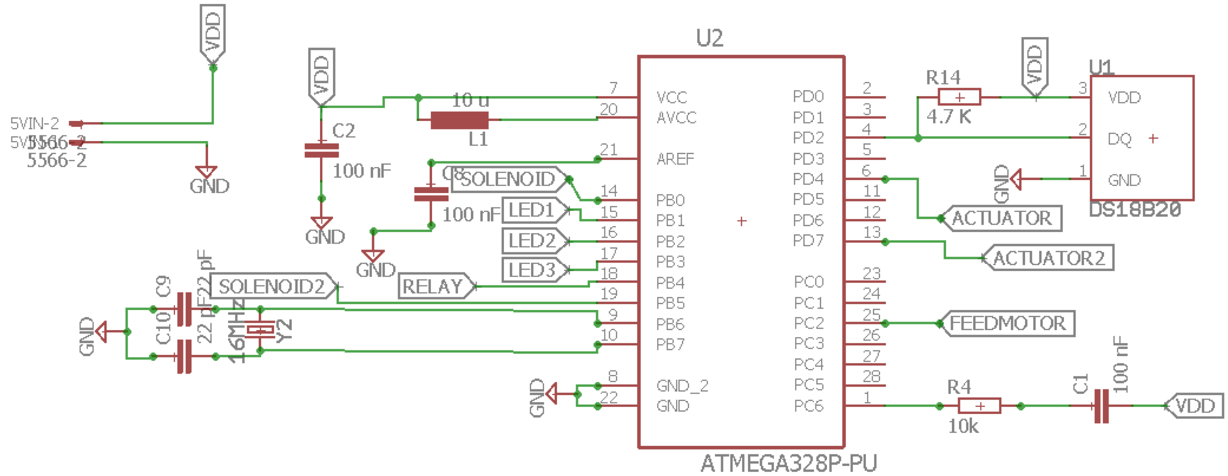

Fig. 3 Microcontroller circuit

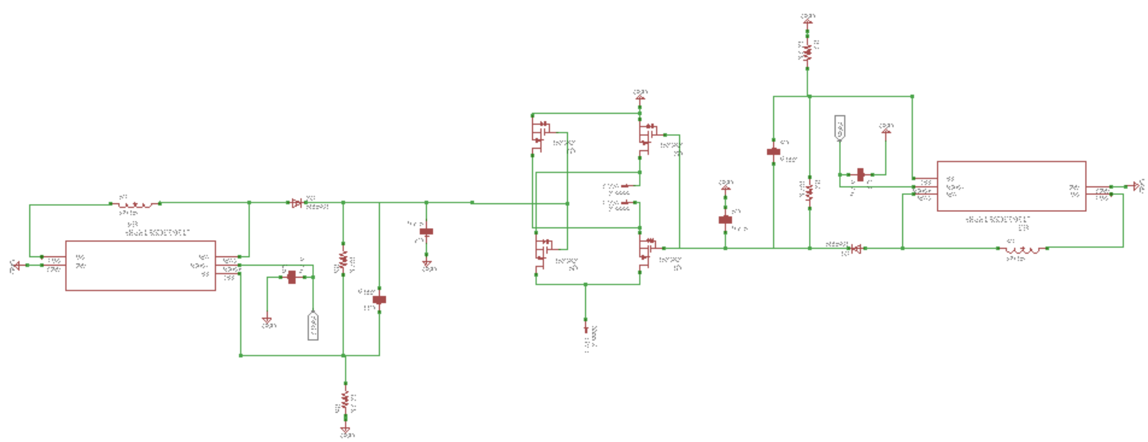

Fig. 4 motor drive circuit

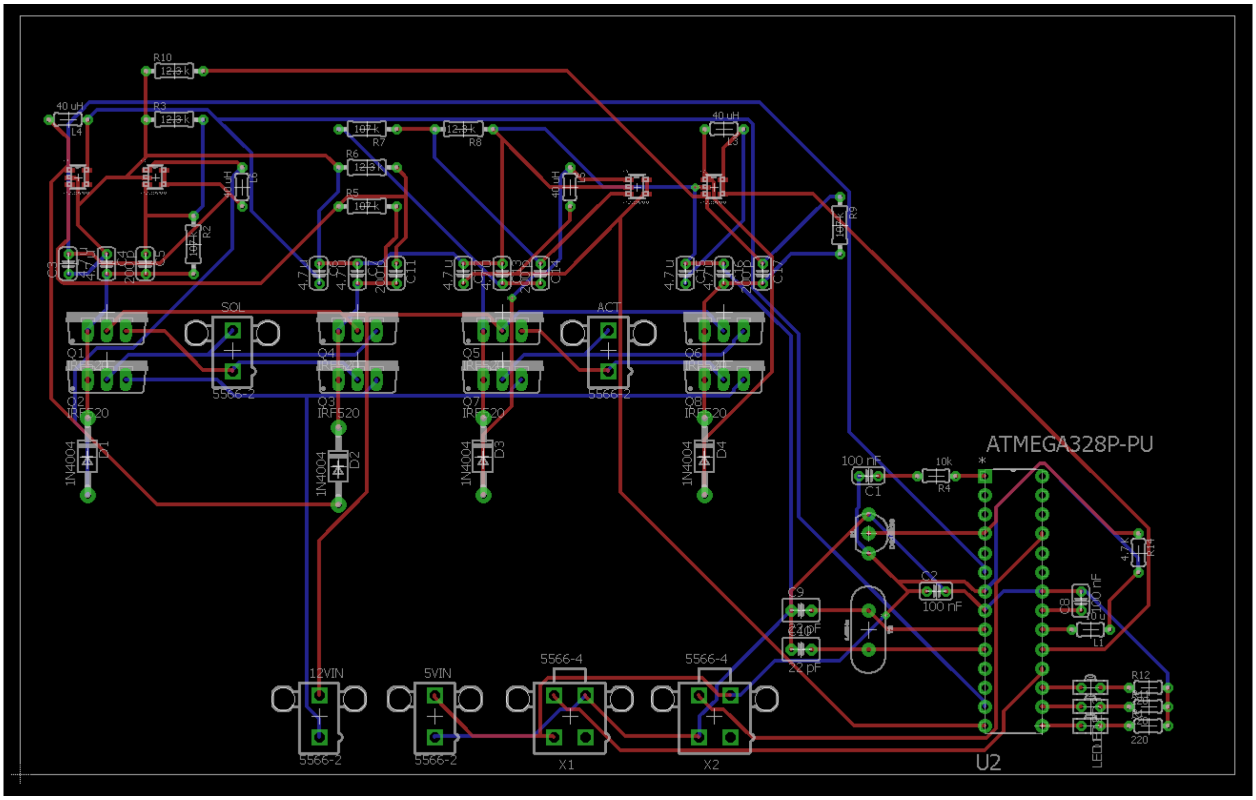

Fig. 5 PCB Layout

2.3.3 Physical Design

Due to the nature of the project, having a robust and function mechanical design was imperative to success. The physical design went through a number of changes prior to the finished product. Figure 6 shows a rough sketch of the design during one of the intermediate steps, whilst figure 7 shows the finished product. One difference between the two figures is the use of a feed motor for the coffee grounds in place of a solenoid valve. This change was made due to availability of parts for testing purposes.

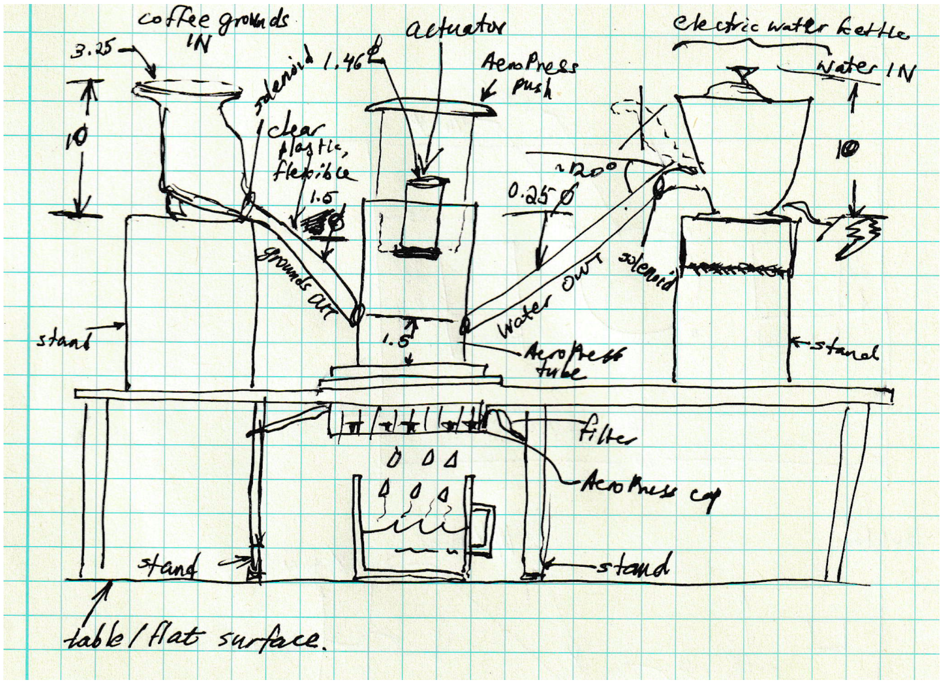

Fig. 6 rough sketch of the physical design of the product

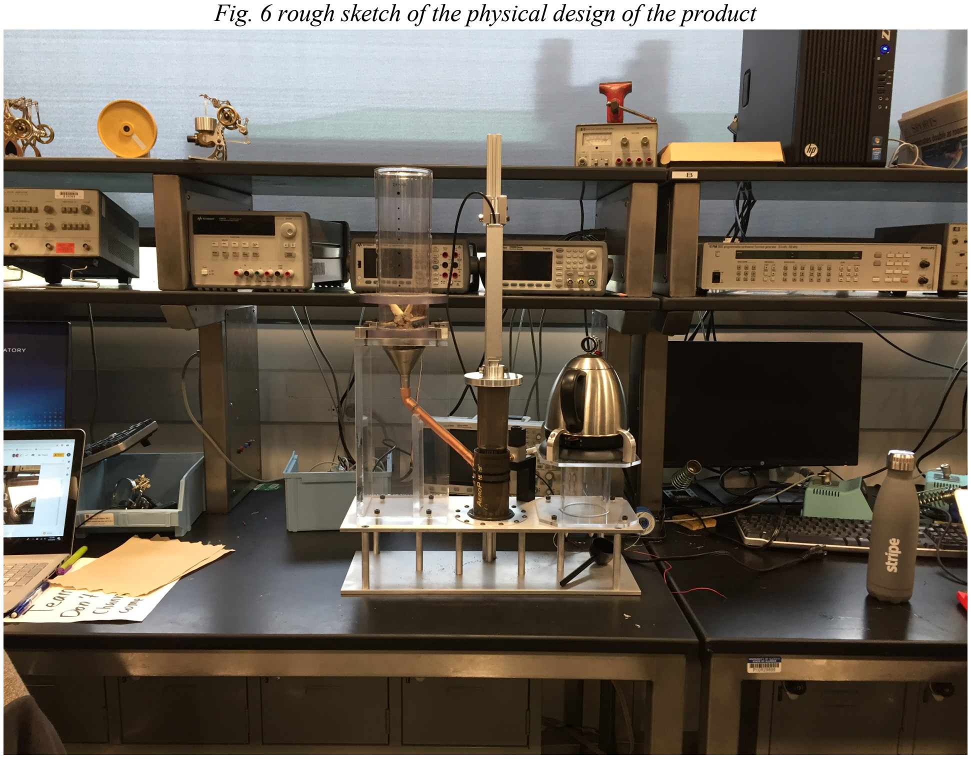

Fig. 7 the finished product

2.4 Simulations and Calculations

2.4.1 Boost Up Circuit

The boost up circuit is essential to controlling the actuator with the ATmega328P. The ATmega328 outputs at around 5 V, however the actuator is rated at 12 V. To reconcile this discrepancy, the output voltage of the ATmega328 needs to be stepped up to 12 V. This step-up control is done through the use of a boost converter IC.

The actuator driver circuit shown above was simulated in LTSpice. The actuator is modeled as an inductor in series with a resistor here. This model is a reasonable approximation for a DC motor. The current provided to the actuator is limited by the internal resistance of the actuator in the steady state.

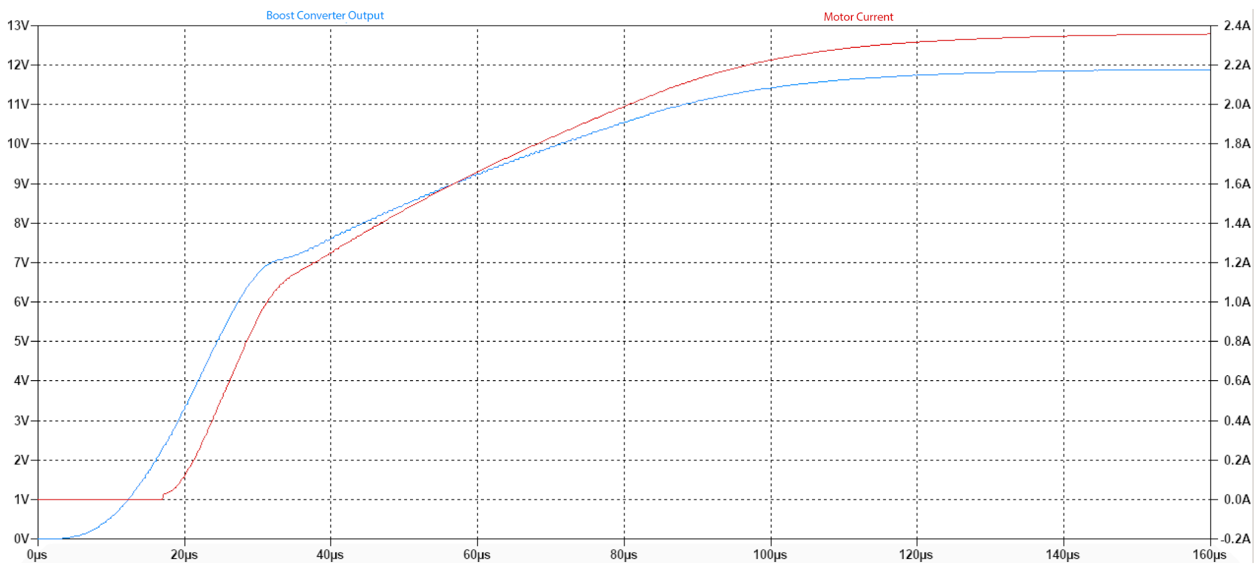

Fig. 8 Plot of the boost converter output voltage and motor current versus time for a "high" output from the ATmega328.

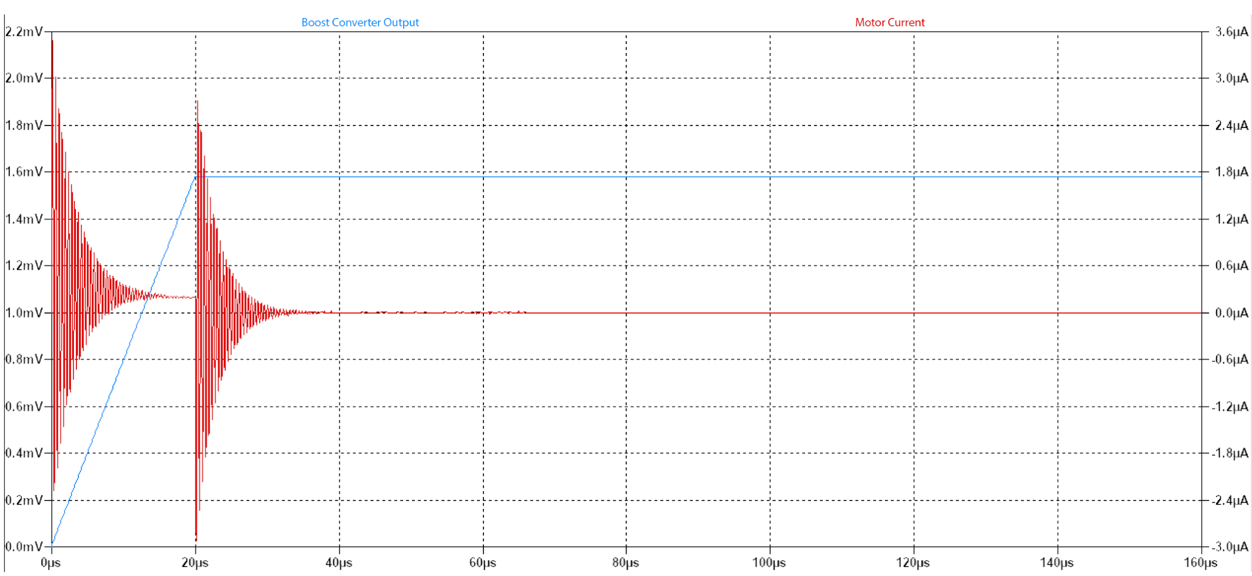

Fig. 9 Plot of the boost converter output voltage and motor current versus time for a "low" output from the ATmega328.

2.4.2 Actuator

As mentioned previously, the main purpose of the actuator is to apply force to the plunger to press it down. Pressing the plunger down into the water will cause pressure to build in the press pot, however since this project is not an automated espresso machine, the amount of pressure applied to the water is not a highly controlled variable. The primary concern is that the actuator is able to apply enough force to press the plunger. Under normal operation the AeroPress can have 0.35 – 0.75 bar of pressure in the press pot [5]. This pressure can be used—along with the diameter of the AeroPress [6]—to extract the required force.

$$P = \frac{F}{A}$$

$$F = P \cdot A \approx (10.87783\ psi)[\pi(\frac{2.5\ in}{2})^2] \approx 53.4\ lbf$$

Due to the fact that 0.75 bar is an upper bound on the pressure in the press pot, a 50 lbf actuator will be used in place of a 53.4 lbf actuator due to availability of parts. This calculation leaves the maximum pressure in the pot as:

$$P = \frac{50}{[\pi(\frac{2.5}{2})^2]} \approx 10.2\ psi \approx 0.7\ bar$$

3. Costs

3.1 Labor

A reasonable salary for an ECE@Illinois graduate would be $40/hour. There are three members in our group, and we each put in approximately three hours of work for 16 weeks. At this rate, our labor cost is $40/hour x 2.5 x 3 hr/wk x 16 wk = $4,800.

3.2 Parts

Item	**Manufacturer**	**Part No.**	**Cost ($)**
AeroPress	AeroPress	83R20	29.95
Microcontroller	AtMel	ATmega328p	0.84
Temperature sensor	Dallas Semiconductor	Sparkfun DS18B20	11.95
Actuator	SOViK	S100-100-12-15	53.99

Kettle	Aicok	Electric Gooseneck Kettle	18.67
Power MOSFET	STMicroelectronics	STP90NF03L	1.36 (x8)
Boost converter	Linear Technologies	LT1613CS5#TRMPBF	4.25 (x4)
Crystal oscillator	Sparkfun	COM-00536	0.95
Solenoid valve	Joyway	JWDCF2V025-06	10.59
Power cord		PW101-1206	1.86
Relay	NewZoll	B01N3LGV7J	7.59
Resistors	Mouser	293-VAL-RC	0.07 (x 12)
Inductors	Bourns inc.	M8658-ND	1.08 (x 3)
Capacitors	Mouser	1C20Z5U104M050B	0.16 (x 12)
Diodes	Allied Electronics	1N5819	0.38 (x 4)
Total			171.79

In total, the cost is $4,800 + $171.79 = $4971.79. If, say, 10,000 units are sold, the amortized cost by splitting the labor amongst the units is $4.80 + $171.79 = $176.59.

3.3 Schedule

The following time-table shows our progress, by week.

Week	Sachin Parsa	Justin Yang	Brandon Eubanks
1/14	Brainstorming for Ideas	Brainstorming for Ideas	Brainstorming for Ideas
1/21	Work on the RFA	Work on the RFA	Work on the RFA
1/28	Finalize proposal	Research the microcontroller required for the project	Research the mechanical aspect of the project
2/4	Learn the functionality of Eagle	Start plan for the design document	Learn the functionality of Eagle

2/11	Work on the introduction and help Brandon with the design portion of the design document	Work on the cost, schedule and the ethics and safety portion of the design document.	Work on the functionality portion of the design document
2/18	Calculate the requirements needed for the parts in the pressure subsystem	look into the supporting circuitry for the microcontroller	Research how the power would be supplied to actuator and microcontroller
2/25	Talk to the TAs and finalize the physical design	Start designing the software required for the circuit	Finalize the power subsystem
3/4	Submit final physical design to the machine shop	Software design for the project	Finalize the part needed and order parts
3/11	Prototyping press subsystem and the solenoid subsystem	Test temperature sensor and write software for control	Prototyping temperature control circuit
3/18	Making circuit schematics on Eagle	Continue software design for the project	Prototyping the feed motor circuit
3/25	Making Circuit schematics and final breadboard tests	Start testing code on LCD display	Making Circuit schematics and final breadboard tests
4/1	Order the PCB	Continue software design and testing	Finish PCB layout
4/8	Solder PCB and test various components	Continue software design and testing	Solder PCB and test various components
4/15	Finish soldering and order any last minute parts	Continue software design and testing	Finish testing PCB
4/22	Final integration and testing. Prepare for final Demo	Final integration and testing. Prepare for final Demo	Final integration and testing. Prepare for final Demo
4/29	Preparing for final Presentation and paper	Preparing for Final Presentation and paper	Preparing for final Presentation and paper

4. Conclusion

4.1 Accomplishments

In the end, we are able to perform many of the original goals the project set out to accomplish. In particular, we were able to brew cups of coffee one at a time using the built system, where each subsystem performed the manual task.

4.2 Uncertainties

Throughout the process of building the project, there were many uncertainties about the different components of the system. In particular, the physical and mechanical design caused uncertainty with respect to the disposal of the coffee grounds and the water. Due to these concerns, the design is updated to ensure that clogs and other mishaps do not occur. The solenoid for the coffee grounds was replaced with a feed motor, and the dispensing angle was calibrated so as to speed up delivery to the main AeroPress chamber.

4.3 Ethical considerations

There exist some ethical and safety concerns regarding the design and implementation of our project.

Since the coffee machine will be used for making coffee primarily for human consumption, the machine and must have food-grade components. Based on the design of the coffee machine, we will be using food-grade plastics and materials so as not to introduce an excess of harmful chemicals into the acidic coffee solution.

Furthermore, we have to be careful about the safety of the device since we are going to be powering the coffee machine with a voltage source. We expect to use a standard household U.S. (grounded) wall outlet, so we will need to have safety precautions around the usage of power (such as current limiting MOSFETs), to prevent melting the device. We will monitor the pressure and temperature at different areas in the device to ensure that the device does not malfunction. As a standard household kitchen appliance, we need to ensure that the electronic components are encased so that they are water-resistant should a spill or leak occur.

We will test each component of the device in isolation during our build phase to make sure that everything works according to plan before we move to have the components work together.

One of the general ethical principles for the Association of Computing Machinery (ACM) is to “avoid harm”[7], including “unjustified physical or mental injury”[7]. The operation of our device involves electrical equipment, so we will ensure that in a commercial or user environment that appropriate warning, notices, and safeguards are placed on or made available prior to the operation of the device to ensure that appropriate care is taken. Furthermore, the product of our device produces hot coffee, which under certain conditions can be “dangerously hot”[8]. For the safety of the ultimate consumer, the coffee machine will carry warnings and be designed appropriately so as to minimize the risk associated with the consumption of coffee.

4.4 Future work

In the future, there are many additional optimizations and additions that can be made to the project. Aside from using a new PCB and parts that are not shorted, the project can be improved by allowing for using whole beans. That is, a coffee grinding subsystem can be added that grinds whole beans into the container for the coffee grounds, allowing for fresher coffee.

Additionally, another addition can be about allowing for user-defined pressure. Since the pressure in the AeroPress chamber greatly affects the taste of the coffee, another degree of control for the actuator will allow for more precise control in the taste of the coffee.

Finally, the project can also be improved by integrating a voice–user interface (VUI), such Amazon Alexa or Google Assistant. The integration of a VUI would allow for a more seamless interface, where the user can ask anywhere—including out of the kitchen—for a cup of coffee to be brewed. The VUI could also allow for other integrations with rest of the ecosystem, allowing for increased automation and discoverability.

References

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Appendix A: Requirement and Verification Table

Requirement	Verification	Y/N
Grounds 1) Must be able to fed into the chamber using the feed motor.	**Grounds** 1) a) The feed motor turns on after the coffee grounds are fed in. Verify that it turn on. b) Feed coffee grounds into the feed motor pipe and verify that they come out the bottom.	**Y**
H-Bridge 1) Must supply 2 +/- 1 A to the actuator under a realistic load	**H-Bridge** 1) a) Manually fill the AeroPress with water and coffee grounds. b) Forward bias the leads on the actuator to begin the press. c) Using an ammeter, measure the current flowing through the H-Bridge.	**Y**
Boost Converter 1) Able to to supply 12 V to the gate of the power MOSFET	**Boost Converter** 1) a) With the help of the multimeter probe the ends of the gate to check if the boost circuit works.	**Y**
User Interface 1) Button press is registered in the software 2) LCD display shows text	**User Interface** 1) a) Use button unit test software. b) Connect button. c) Press button. d) Button press shows up in the software terminal. 2) a) Use LCD unit test software. b) Connect LCD. c) LCD displays test texts.	**N**
Water (software) 1) Temperature is read in software 2) Kettle heats up and stops at desired temperature	**Water (software)** 1) a) Use temperature unit test software. b) Connect temperature sensor. c) Measure temperature. d) Temperature value, as compared with thermometer, shows up in the software terminal. 2) a) Use relay module unit test software. b) Connect relay module. c) Measure voltage on Normally Open (NO).	**Y**
Grounds (software)	**Grounds (software)**	**Y**

1) Feed motor can be controlled by software.	1) a) Use feed motor unit test software. b) Connect feed motor. c) Feed motor turns as desired.	
Actuator (software) 2) Actuator can be controlled by software.	**Actuator (software)** 2) a) Use actuator unit test software. b) Connect actuator. c) Actuator moves forward and backward as desired. d) Limit switch hits show up in software terminal.	**Y**
Relay Module 1) Module is able to switch wall power to the water kettle	**Relay Module** 1) Connect ground and Vcc to respective outputs of a power supply on a breadboard 2) Connect an ohmmeter between the COM and NO terminals of the relay module 3) Switch the input terminal between high and low voltage and note the resistance. If COM and NO are connected, the resistance should go from OL to a lower value.	**Y**
H-Bridge 1) Must supply 2 +- 1 A to the solenoid under a realistic load	**H-Bridge** 1) a) Forward bias the leads on the solenoid to open the solenoid. b) Using an ammeter, measure the current flowing through the H-Bridge.	**Y**
Boost Converter 1) Able to to supply 12 V to the gate of the power MOSFET	**Boost Converter** 1) a) With the help of the multimeter probe the ends of the gate to check if the boost circuit works.	**Y**