Automated Specialized Coffee Machine

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1 Introduction

1.1 Objective

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% value share [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]. Specialty coffee has become more popular as it states that for all the cups of coffee consumed, 59% of those cups were specialty versus 41% non-specialty [3]. These statistics suggest that the American people are obsessed with drinking specialty coffee. The problem that they face is that the process of making specialized coffee like the French press and AeroPress takes a lot of effort, time and precision.

We plan to make the process of making a cup of AeroPress coffee completely automated, which would save individuals time, and effort every morning. Our design for the automated AeroPress consists of two main subsystems: boiling the water and extracting the coffee. The subsystem for the boiling of water will be user temperature controlled and set to five-degree increments. The subsystem for extraction of coffee will pump the water and the coffee beans together and push the plunger which will produce the cup of coffee. While there are many existing coffee machines on the market, our solution will be focused on making high-quality AeroPress. We seek to create a low-cost product that can produce quality coffee with the user desired settings.

1.2 Background

Automated coffee machines cost anywhere from $200 to about $10,000. There are also no machines which make AeroPress. Coffee machines are primarily oriented for cappuccino and espresso. The more selective coffee drinkers prefer specific specialized coffee like the AeroPress. We plan to give the user of this product, enough control to customize according to their preference. In the process, the user will be able to select the temperature of the water being boiled and would also be able to insert the grinded coffee beans. The system we propose creates an affordable way for individuals to automate the bothersome process of making specialized coffee.

1.3 High-Level Requirements

- 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.
2 Design

2.1 Functional Overview

The making a cup of 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 performing the hot water extraction.

In this project an AeroPress will be used for hot water extraction. The water will be heated in a kettle and gravity fed into the AeroPress. A solenoid valve will open/close a door, allowing ground coffee beans to be delivered to the press. The AeroPress will be pressed by an actuator. Prior to the hot water extraction, the water will be heated to a user-selected temperature. The temperature will be monitored with a temperature sensor and used to control the kettle (i.e., according to the temperature, the kettle will turn on or off).

To reduce the cost and complexity associated with having a custom IC fabricated, a microcontroller (ATMEGA328) will be used to read input from the switches and sensors. The microcontroller will use this information to perform the control flow. Using relay modules [4], it will control the power to the actuator and electric kettle accordingly.

2.2 Block Diagram
Fig. 1. Block diagram for the automated coffee machine.

Fig. 2. Basic circuit diagram showing the actuator driver circuit. The UART output of the microcontroller is amplified (Adafruit A342) and sent to the gate of a power MOSFET.
Fig. 3 Detailed circuit schematic for driving the actuator. Here the actuator is modelled as a resistor in series with an inductor. [6][7]
Fig. 4 Supporting circuitry for the microcontroller. This circuit interfaces the 16 MHz crystal oscillator with the microcontroller [5]
Fig 5. Supporting circuit for the microcontroller. This circuit low pass filters Vcc before passing it to the microcontroller. [5]

Fig. 6 Decoupling capacitor for the analog reference for the microcontroller.
Fig. 7 Reset circuit for the microcontroller. [5]
Fig. 8 Software flowchart for the design.
2.3 Physical Design

Fig. 9. Physical diagram of the project showing the AeroPress in its mount with a coffee mug underneath
Fig. 10
The physical design of this design is particularly important as the project will involve many moving mechanical parts. The main moving parts consist of the coffee grounds, water, and an actuator.

2.3.1 Coffee Grounds
The coffee grounds must be moved into the AeroPress to be extracted. To do this, pre-ground beans will be delivered into the AeroPress by a 3”-diameter chute through a solenoid valve.

2.3.2 Water
The hot water must be transferred from a kettle (used for heating the water) into the AeroPress. The least mechanically complex way to achieve this is to gravity feed the water out of the kettle, through a ½”-diameter solenoid valve, and into the AeroPress.

2.3.3 Actuator
In an AeroPress, the hot water extraction occurs inside the press pot. Similar to a conventional coffee machine, the hot water is used to extract the coffee grounds. The main distinction here is that the AeroPress has a plunger that needs to be pressed, similar to a french press. Unlike a
french press, the water is pressed out of the pot, through a filter, and into a mug. To perform the pressing, and complete the hot water extraction phase, an actuator will be utilized to mechanically press the plunger on the AeroPress. In order to seamlessly mate the plunger and the press pot, the plunger will be on a set of rails. This will allow the actuator to press the plunger directly into the press pot.

2.4 Block Level Requirements

2.4.1 Control/Sensing Subsystem

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature Sensor</strong></td>
<td><strong>Temperature Sensor</strong></td>
</tr>
<tr>
<td>1)  Must use Serial Peripheral Interface (SPI)</td>
<td>1) a) Physically connect the temperature sensor to a single board microcontroller (such as an Arduino Uno).</td>
</tr>
<tr>
<td>2)  Must be precise to 1 degree Fahrenheit</td>
<td>b) Write a simple Arduino program to print the output of the temperature sensor.</td>
</tr>
<tr>
<td></td>
<td>c) Warm water on a conventional stove top.</td>
</tr>
<tr>
<td></td>
<td>d) Place the temperature sensor in the water, and compare with a physical thermometer to verify precision.</td>
</tr>
</tbody>
</table>

2.4.2 Water Heating/Grounds Subsystem

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grounds</strong></td>
<td><strong>Grounds</strong></td>
</tr>
<tr>
<td>1)</td>
<td>a) Construct PVC pipe with vertical shaft and 120 degree pipe elbow</td>
</tr>
<tr>
<td></td>
<td>1)</td>
</tr>
<tr>
<td>1)</td>
<td>a) Construct PVC pipe with vertical shaft and 120 degree pipe elbow</td>
</tr>
</tbody>
</table>
2.4.3 Press Subsystem

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-Bridge</td>
<td>H-Bridge</td>
</tr>
<tr>
<td>1) Must supply 2 ± 1 A to the actuator under a realistic load</td>
<td>1) Manually fill the AeroPress with water and coffee grounds. Forward bias the leads on the actuator to begin the press. Using an ammeter, measure the current flowing through the H-Bridge.</td>
</tr>
</tbody>
</table>

2.5 Simulations and Calculations

2.5.1 Boost Up Circuit

The boost up circuit is essential to controlling the actuator with the ATMEGA328P. The ATMEGA outputs at ~5V, however the actuator is rated at 12V. To reconcile this, the output
voltage of the ATMEGA needs to be stepped up to 12V. This is done through the use of a boost converter IC.

The actuator driver circuit shown above was simulated in LTSpice. The actuator is modelled as an inductor in series with a resistor here. This 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. 13 Plot of the boost converter output voltage and motor current versus time for a “high” output from the ATMEGA
2.5.2 Actuator

As mentioned above, 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 [8]. This can be used (along with the diameter of the AeroPress [9]) to extract the required force.

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

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 leaves the maximum pressure in the pot as:

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

2.6 Tolerance Analysis

2.6.1 Pressure

The pressure-based plunger is a significant risk in our project. The plunger must be able to move smoothly and apply pressure as the arm of the plunger moves. The plunger should be able to make precise, controlled movements due to the desired control necessary in order to keep the coffee beans at the appropriate temperature and pressure. As such, there is some risk associated with the mechanical control for the plunger to move appropriately. Additionally, the pressure sensor in the system needs to properly communicate with the motor control to provide a feedback loop for the plunger movement to appropriately terminate. The sensor output and PCB design will determine how the sensitivity of the plunger functions.

The AeroPress relies on pressure in order to push water through the coffee filter. As one of the most essential components to the design and function of our automated coffee machine, we will
perform tolerance analysis to determine the allowed deviation from our desired values that allow our component to still function.

The pressure subsystem needs to be able to apply enough pressure to be able to push the water through the filter. There are several factors that affect the pressure applied by the piston. The tolerance of the pressure sensor, the temperature of the water, the area of the press and the force applied by the press itself. According to the data of AeroPress we need the pressure that can range from 0.35 bar and 0.75 bar.

The tolerance of the pressure sensor is $\pm \frac{1}{2} \text{hPa} = 0.00012 \text{ bar}$. Ideally our pressure needs to be around 0.75 bar and the tolerance of the pressure sensor should not affect our project.

The range of the diameter of the AeroPress is from 2.5 in to 3 in. The area changes the pressure with this range from 7.55 psi to 10.87 psi, which is 0.52 bar to 0.75 bar. This is again within our tolerance limit as our pressure can range from 0.35 bar to 0.75 bar.

$$P = \frac{F}{A} = 53.4 \text{ lbF}$$

Assuming that the diameter is 3 in. The pressure will become

$$P = \frac{53.4 \text{ lbf}}{\pi \times (\frac{3}{2})^2} = 7.55 \text{ psi} = 0.52 \text{ bar}$$

$$\% \text{error} = \frac{(0.75 - 0.52)}{0.75} \times 100\% = 30.67\%$$

The effect of the change in area is given by the following graph

![Effect of Area on Pressure](image-url)

Fig. 15. Figure showing the effect changing diameter has on pressure
The effect of temperature on the pressure assuming that the volume is constant can be achieved using Charles’ law. The temperature ranges from 175°F to 212°F, assuming the pressure is 0.75 bar at 175°F then the pressure will be 0.619 bar. This is within our range of tolerance as the lower limit is 0.35 bar.

\[
\frac{P_1}{P_2} = \frac{T_1}{T_2}
\]

\[
P_1 = 0.75 \text{ bar (175°F/212°F)}
\]

\[
P_1 = 0.619 \text{ bar}
\]

\[
\% \text{error} = \frac{(0.75 - 0.619)}{0.75} \times 100\% = 17.46\%
\]

This mechanical system must be resilient to wear and tear due to continued usage, especially considering that the system contains moving parts. Certain components, such as coffee filters, are designed to be used and replaced. In other cases, we can prototype and secure once we have the final physical design appropriately configured.

### 2.6.2 Motor Current

As mentioned above, the steady state current through the actuator is dependent upon the internal resistance of the actuator. This is simply a consequence of Ohm’s law leading to less voltage dropped across the transistors (i.e. lower Vds) when the actuator resistance is raised. This could be potentially problematic for a sufficiently low actuator resistance, as the current could potentially surpass the 3 amp rating of the actuator. The critical value is best found through simulation as transistors are nonlinear devices, which leads to tedious hand calculations.

![Fig. 16 Plot showing the motor current versus time for an internal resistance of 3.1Ω.](image)
As can be seen in the above plot, the current goes slightly above 3A for an internal resistance of 3.1 Ω. If the internal resistance of the actuator is 3.1 Ω or lower, a current limiting resistor will need to be placed in series with the actuator motor. A fuse should also be placed in series with the actuator motor to prevent damage to the device.

3 Cost and Schedule

3.1 Labor
A reasonable salary for an ECE@Illinois graduate would be $80. 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 $80/hour x 2.5 x 3 hr/wk x 16 wk = $9,600.

3.2 Parts

<table>
<thead>
<tr>
<th>Item</th>
<th>Part No.</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AeroPress</td>
<td>83R20</td>
<td>29.95</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>ATmega328</td>
<td>0.84</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>Sparkfun DS18B20</td>
<td>11.95</td>
</tr>
<tr>
<td>Actuator</td>
<td>Homend GR9863</td>
<td>36.95</td>
</tr>
<tr>
<td>Kettle</td>
<td>HOMIGRAND 1L Electric Gooseneck Kettle</td>
<td>18.67</td>
</tr>
<tr>
<td>Power MOSFET</td>
<td>STP90NF03L</td>
<td>1.36 (x4)</td>
</tr>
<tr>
<td>Boost converter</td>
<td>LT1613CS5#TRMPBF</td>
<td>4.25 (x2)</td>
</tr>
<tr>
<td>Crystal oscillator</td>
<td>Sparkfun COM-00536</td>
<td>0.95</td>
</tr>
<tr>
<td>Solenoid valve</td>
<td>JWDCF2V025-06</td>
<td>10.89 (x2)</td>
</tr>
<tr>
<td>Power cord</td>
<td>PW101-1206</td>
<td>1.86</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>118.22</td>
</tr>
</tbody>
</table>
In total, the cost is $9,600 + $100.2 = $9700.20. If, say, 10,000 units are sold, the amortized cost by splitting the labor amongst the units is $9.60 + $100.20 = $109.60.

### 3.3 Schedule

The following time-table will show our ideal progress, by week.

<table>
<thead>
<tr>
<th>Week 1</th>
<th>All: Begin Brainstorming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 2</td>
<td>All: Come up with initial idea and get idea approved</td>
</tr>
<tr>
<td>Week 3</td>
<td>All: Work on proposal</td>
</tr>
<tr>
<td>Week 4</td>
<td>All: Finalize proposal, do discovery on work needed and specific external requirements</td>
</tr>
<tr>
<td>Week 5</td>
<td>All: Learn Eagle software, work on design document</td>
</tr>
<tr>
<td>Week 6</td>
<td>All: Work on design review</td>
</tr>
</tbody>
</table>
| Week 7 | Brandon: Power system  
Justin: Control System  
Sachin: press system and integration |
| Week 8 | Brandon: power system  
Justin: software design and PCB  
Sachin: hardware design and PCB |
| Week 9 | Brandon: work with machine shop on physical components for press  
Justin: Finish PCB  
Sachin: continue integration |
| Week 10 | Brandon: temperature control  
Justin: water system control  
Sachin: test press system |
| Week 11 | Receive PCB  
Brandon: test temperature and water control  
Justin: solder PCB  
Sachin: test PCB functionality |
<p>| Week 12 | All: test PCB, finalize design |</p>
<table>
<thead>
<tr>
<th>Week 13</th>
<th>All: finalize design, testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 14</td>
<td>All: prepare mock demo</td>
</tr>
<tr>
<td>Week 15</td>
<td>All: prepare demo</td>
</tr>
<tr>
<td>Week 16</td>
<td>All: prepare paper</td>
</tr>
</tbody>
</table>

4 Ethics and Safety

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”[10], including “unjustified physical or mental injury”[10]. 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”[11]. 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.
References:


