Rebirth of a 60's Icon: A Brighter, Safer, Faster Heating Lava Lamp

Devin Bryant

Matthew Romano

Daniel Frei

Final Report

ECE 445, Senior Design, Fall 2016

TA: Jamie Norton

7 December 2016

Project No. 13

Abstract

The lava lamp is a cultural icon and a beloved decorative piece present in many homes. However, while many people own a lava lamp, in general lava lamps do not see much everyday use. There has been virtually no change to the its original design in the 1960's. Furthermore, it is often dim and takes an hour or more to begin working. In this paper, we demonstrate how a lava lamp design that possesses uncoupled heating and lighting systems can be employed to heat more quickly and provide more enjoyment to the user. And with a temperature regulation control scheme the lava can not only be more fun but also be more safe.

Contents

1 Introduction

1.1 Motivation and Purpose

The lava lamp was, and still is to a lesser degree, a popular piece of lighting decor that was developed in the 1960's. Its shape is similar to that of the Saturn rocket that was used during that era to take the United States to the moon. Also similar to that period of history is its internal contents which move slowly and dynamically to create a psychedelic mood [1].

Over the years the lava lamp has become a somewhat kitsch piece of technology. For being a lamp it doesn't actually give off much ambient light, and its base design hasn't changed very much since its inception. Not only does it look outdated, but it also takes at least an hour or two (depending on individual lamp properties) for the wax inside of the lamp to start moving the way it is supposed to. Once operational it will only work as intended for a few hours before the lamp gets too hot and disrupts the wax dynamics. Users actually have to plan ahead for when they want to look at their lava lamp. Furthermore, lava lamps can be very hot to the touch which presents a safety hazard.

The technical aspects of the traditional lava lamp are straightforward. It is comprised of a sealed glass bottle, containing a certain type of liquid and small amount of wax, which sits near the top of a 40 W incandescent light bulb. The heat from the bulb very slowly melts the wax and also heats the internal liquid. When the wax melts it expands which reduces its density. As a result the melted wax floats to the top of the bottle. While it ascends it begins to cool, increase its density, and eventually returns back to the bottom.

Our project handles the problems of the traditional lava lamp by decoupling the lighting and heating mechanisms. Where the traditional lamp uses an incandescent bulb for both light and heat, our model uses a controlled 100 W heating resistor array and a double 350 mA RGBW light-emitting diode (LED) array. This separation allows us to control the temperature of the lamp without disrupting the amount of light provided. Moreover, the upgrade to high power multicolored LEDs allows us to change the color of the lamp. Traditional lamps can only control the color by having colored liquid or glass which cannot be changed dynamically.

Our upgrade to 100 W from 40 W also grants us the ability to heat the lamp significantly faster. In fact we can achieve initial movement of the wax in one-third of the time of a traditional lava lamp. There is still a significant heating phase due to precautions relating to heat transfer safety, but users will no longer have to schedule an appointment for their desk appliances. And since we can control our heat source we are able to keep the lava lamp within the ideal operating temperatures–not too hot and not too cold.

1.2 Objectives

User Requirements

- Reaches operational temperature at least 25% faster than traditional lamps.
- Thermal regulation prevents the product from reaching unsafe temperatures.
- Provides more ambient light than traditional lava lamps.
- Dimmer switch adjusts light levels and mode buttons select distinct pre-programmed color modes.

Product Features

- Starts working 50% faster than other models.
- Maintains temperature setting for at least 9 hours.
- Easily plugs into any standard U.S. outlet.
- User can adjust light brightness and color.
- Interesting and attractive conversation piece.

1.3 Block Diagram and Descriptions

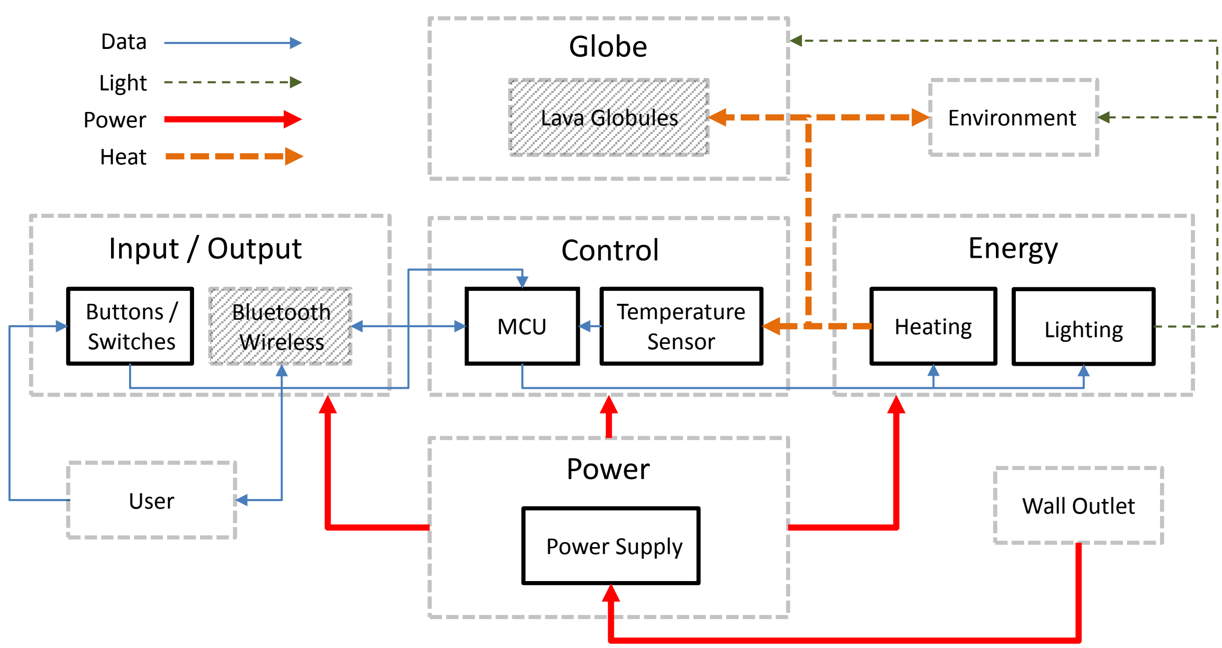


Figure 1: Lava globe block diagram

Our project consists of many modules as shown in Figure 1, but the modules that received most of our attention were the Power Supply, Heating, Lighting, Temperature Sensor, Microcontroller (MCU), and Buttons/Switches modules. The Bluetooth Wireless and Lava Globule modules were out of the scope of this project.

Power

Power Supply

Power from a wall outlet is passed to our power supply via a 20 V AC-to-DC power supply. The 20 V signal is then regulated to appropriate levels and distributed. An LM2677 buck converter sends up to 6 V at 5.6 A to the lighting system, and an LM317 linear voltage regulator sends 3.3 V to the control components such as the MCU, temperature sensors, and on-unit input. The heating system can draw up to 20 V at 5 A directly from the power supply depending on the thermal needs of the lamp.

We have fairly tight tolerance requirements on our 6V power to the lighting module: since the current through the LEDs is controlled by resistors, overvoltage conditions could damage the LEDs by causing too much current to be drawn. Since up to 85% of the voltage drop is over the LED and NMOS (in the case of the green channel), and not the limiting resistor, a 20% rise in voltage over 6V can lead to over 130% rise in current. Thus we set a required maximum of 6.2V, a 3.3% rise, to ensure optimal operation of our LEDs.

Energy

Heating

The heat source receives a pulse width modulation (PWM) signal from the MCU and up to 100 W of power from the power supply. The heat source consists of a PSMN022-30PL n-channel metal-oxide-semiconductor field-effect transistor (MOSFET) which handles the PWM signal, and an array of four parallel 16 Ω / 25 W power resistors thermally linked via thermal paste to an aluminum heat spreader cup. This cup holds the glass lava lamp bottle and spreads the heat evenly across the bottom of the glass. The PWM signal from the MCU is used to control how much heat is produced by the power resistor array for both safety and functionality.

The power, and thus heat, can range from 0 W to 100 W depending on the duty cycle issued by the MCU. Another feature of the heat source is that the heat resistors are housed within a thermal isolation container made from refractory board. This container helps channel heat into the heat spreading cup which not only increases heat efficiency but also protects other electronics from unwanted thermal effects such as LED brightness dependency on temperature.

Lighting

The light source receives four PWM signals from the MCU and up to 16.8 W from the power supply. The PWM signals are applied to four PSMN022-30PL n-channel MOSFETs. Each MOSFET controls the brightness of a single color channel (red, green, blue, or white) for two CREE XLamp XM-L Color LEDs. The light provided by the LEDs is directed through a physical channel (shown in Figure 11 Appendix B) through the aluminum heat spreader to the base of the glass bottle illuminating the contents and nearby environment.

The LEDs are protected from the high temperature of the heat source by the thermal isolation container, but do produce their own heat. At our expected operating temperature of 150°F the RGBW light output should be 74%, 91%, 97%, and 91% respectively [2], so with the exception of the of red channel we are able to maintain most of our light integrity even in the event of heat leakage.

Control System

MCU

This module, the ATmega328P MCU, receives 3.3 V from the power supply, analog voltage signals from the temperature sensors, as well as analog and digital from the sliding potentiometer and button of the input/output module respectively. The temperature sensor information is used in a feedback loop to determine how much power to give the heating element, via PWM signals, thereby adjusting the heat output. The input/output information tells the MCU to either switch color modes or adjust the brightness of the LEDS. The ATmega328P sends data to both the heating and lighting elements as explained in their corresponding block descriptions.

Temperature Sensor

For this module we used two TMP36 temperature sensors. These sensors are analog, linear, and calibration free [3]. They are powered by 3.3 V via the power supply. The first sensor is thermally epoxied to the bottom of the heat spreader millimeters away from the heating resistors. The heating element sensor is thermally epoxied to the the heat spreader plate, millimeters away from the heating resistors. This provides us with a fairly accurate reading of what temperature the bottom of the glass bottle is exposed to. The second sensor measures the external temperature of the glass bottle. The data from these sensors are passed to the MCU for processing. The data from the first is primarily for safety whereas the data from the second is primarily for functionality.

Input / Output

Buttons / Switches

The on-unit input receives power from the power supply and input from the user. The user provides the input by pressing a button to change the lighting color mode or by sliding a potentiometer to change the overall brightness of the lamp. This input is then sent to the MCU for processing.

2 Hardware Design

2.1 Circuit Descriptions

Power Supply

The power board schematic is shown in Figure 4 Appendix B. This module has three destinations for power: heating element, LED lighting, and MCU. Power is passed to the heating element directly, but the LED lighting and MCU need reduced voltages. We chose an LM2677 switching buck converter, set with appropriate feedback resistors (1 kΩ and 3.92 kΩ) to regulate a 6 V signal to the LEDs. The LM2677 can regulate up to 5A of current on its output with the appropriate output inductor and capacitor.

This 6 V signal is further reduced to 3.3 V via an LM317 linear regulator. The LM317 can cheaply output clean power, and results in a simple design. Since the currents are low, the efficiency is not important and the LM317 is appropriate. Again, appropriate feedback resistors (240 Ω and 392 Ω) are used to set the voltage. This 3.3 V signal is then sent to the MCU to power the MCU itself as well as the temperature sensors, button, and slider.

Heating Element

Since heat is the primary factor for lava lamp starting speed and conventional lava lamps use 40 W incandescent light bulbs, we felt it was necessary to greatly exceed 40 W. Therefore, our heating element is comprised of a network of four parallel $16\,\Omega$ / $25\,\mathrm{W}$ power resistors in series with an n-channel MOSFET. This gives us a controllable 100 W heating supply. A schematic of the circuit can be seen in Figure 5 Appendix B.

We chose the PSMN022-30PL n-channel MOSFET because it is capable of handling up to 30 V and 30 A. The heating element can use up to 20 V and 5 A so this rating was critical. Additionally, n-channel MOSFETs are simple to use with our configuration. Unlike a bipolar junction transistor (BJT), an n-channel MOSFET does not require a current limiting resistor. Instead, we use the PWM voltage from the MCU directly.

As an alternative to power resistors we could use an infrared or inductive heating source. Unfortunately, glass reflects infrared radiation so we chose not to pursue that path. We thought inductive heating was a little too complex for this semester, but is an promising idea we would like to investigate in the future.

LED Lighting

Brightness and color was an important part of this project so we chose to use high powered multicolored LEDs. The LED schematic is shown in Figure 6 Appendix B. The lighting is supplied by two 350 mA LEDs that have four (RGBW) color channels. Each LED can supply over 200 lumens with all channels at max power for a total of over 400 lumens of total light [2]. This is comparable to a typical 40 W incandescent bulb [4]. Each color channel is controlled by an n-channel MOSFET which allows us to achieve any color we desire. Finally, the color channels for each LED have a current protection resistor.

Temperature Sensors

The temperature sensor schematic is shown in Figure 7 Appendix B. There are two TMP36 temperature sensors. One is thermally epoxied to the heat spreading plate near the heating resistors and the other is thermally epoxied to the the glass container. Some alternatives to the analog TMP36 are digital sensors and thermistors. We chose the TMP36 because of their simplicity. Specifically, the analog voltage reading provided is linear with respect to the temperature in degrees Celsius, which reduces the computational load of the MCU. Also, there are only three connections and it is calibration-free while meeting our accuracy requirements.

MCU

The MCU schematic is shown in Figure 8 Appendix B. The primary component is the ATmega328P, which controls the logic of the lamp. We chose this chip because it is well known, recommended, and easily meets our requirements. Five of the six available PWM outputs are in use to drive the four LED color channels and the heating element. An ISP header and reset button are made accessible for programming, and also headers for connections to other boards are present.

Input / Output

The input / output module is comprised of an analog sliding potentiometer that adjusts the brightness of the LEDs and a digital tactile button for switching LED color modes. As the potentiometer slider moves across the device, the output voltage interpolates between the voltages at both ends (3.3 V and GND). The MCU then reads this voltage to compute the brightness. Similarly, the button is either closed and connects 3.3 V directly to the MCU input or is open and a pull-down resistor provides GND to the MCU. We chose these types of input mainly for convenience and availability, as well as user experience.

2.2 Calculations

Power Supply

We know that the the LEDs are designed to draw 350 mA per channel. Using Equation 1, with eight channels and 6 V supplied to the LED module, we must provide 16.8W. Since we are using a switching regulator with an efficiency of about 80% [5], this adds about 16.8 W / 0.8 = 21 W to our total system demand. Our heating element is designed to output an absolute maximum of 100 W drawn directly from the 20 V supply, and the other low-power components are negligible in terms of their load. Thus, we needed at least a 121 W 20 V DC supply. We chose a 135 W laptop power adapter as a common product that meets these requirements.

$$P = IV = (8 \times 350 \text{ mA}) \times 6 \text{ V} = 16.8 \text{ W} \tag{1}$$

To provide a 6 V supply, we used a switching regulator. It has adjustable voltage regulation set by feedback resistors. From the datasheet, we see that a common R1 value is 1 kΩ [5]. Equation 2 (also from the datasheet) is used to calculate R2:

$$R2 = R1(\frac{V_{out}}{V_{FB}} - 1) = 1\,\text{k}\Omega(\frac{6\text{ V}}{1.21\text{ V}} - 1) = 3.96\text{ k}\Omega \approx 3.92\text{ k}\Omega \tag{2}$$

To provide a 3.3 V supply, we used a linear regulator. It has adjustable voltage regulation set by feedback resistors. From the datasheet , we see that a common R1 value is 240 Ω [6]. Equation 3 (also from the datasheet) is used to calculate R2:

$$V_O = V_{ref}(1 + \frac{R_2}{R_1}) + I_{ADJ} \times R_2 \tag{3}$$

The datasheet also explains that in most cases $I_A DJ$ can be ignored as negligible. Since the 3.3 V output is consumed by parts with large tolerances, we reduce Equation 3 and solve for R2:

$$R_2 = R_1(\frac{V_O}{V_{ref}} - 1) = 240\ \Omega(\frac{3.3\text{ V}}{1.25\text{ V}}) = 393.6\ \Omega \approx 392\ \Omega \tag{4}$$

Heating Element

Since traditional lava lamps use a 40 W incandescent light as their heating source we want our heating element to produce *at least* 40 W of power. This means that each resistor must supply at least 10 W of power to heat independently. We used the Riedon UAL-25 to provide 25 W per resistor. This brought us to a grand total of 100 W. To find the necessary resistance we used Equation 5.

$$P = \frac{V^2}{R} \tag{5}$$

At our maximum provided voltage of 20 V the resistance should be 16 Ω to achieve 25 W of power. The calculated maximum current traveling through each resistor would thus be 1.25 A found by using the Equation 6:

$$V = IR \tag{6}$$

Since the four heating resistors are in parallel, the current would need to be quadrupled to 5 A at maximum power. Our power supply can offer almost 7 A max, so there is more than enough power remaining for the

LEDs.

LED Lighting

The CREE XLamp XM-L Color LEDs operate at 350 mA and the RGBW channels use 2.25 V, 3.3 V, 3.1 V, and 3.1 V respectively [2]. Our n-channel MOSFETs have variable voltage drops depending on the voltage supplied at the gate. However, at max output the voltage is negligible since the NMOS have milli-Ohm scale resistance [7]. We assume that negligible voltage for our calculation. Since we are providing 6 V to our LED circuit we can find the necessary resistance for the LED protection resistors by using:

$$V_R = 6 \text{ V} - \textit{Channel Voltage} \tag{7}$$

Equation 7 tells us that voltage across the RGBW resistors will be 3.75 V, 2.7 V, 2.9 V, and 2.9 V respectively. Then, by using Equation 6, we can see that the RGBW protection resistor resistances should be 10.7 Ω, 7.7 Ω, 8.3 Ω, and 8.3 Ω respectively. At these resistances Equation 5 tells us that the RGBW protection resistor power dissipation requirements will be 1.3 W, 0.9 W, 1.0 W, and 1.0 W respectively.

2.3 Lava Lamp Base

The base of the lava lamp is designed to house all of the internal components in addition to providing stability to the lamp. This part of the project is truly a multi-collaborative effort. We worked with Skee G. Aldrich and Scott A. McDonald at the ECE building machine shop to work on the best design with available parts and tools. Our base is made from aluminum and has three vertical stages separated by metal plates and standoffs. A sampling of the of the parts described below can be seen in Figures 10 - 13 Appendix C.

The bottom stage houses the PCB and all of the wires. The PCB layer is covered with a metal LED plate which acts to keep the LEDs in place and doubles as an additional heat sink for the LEDs. It contains two large channels to run the LED wires from the PCB to the LEDs and four large holes to run power wires to the next stage–the heating chamber.

In the heating chamber our four power resistors are thermally linked and bolted to the aluminum heat spreading cup. This cup is then housed within refractory board, a thermal isolation material, which serves to focus heat to its intended target. The bottom of the refractory board is etched such that the LEDs have a small chamber to reside and the whole refractory board cup lays flush with the LED plate. The heat spreader and refractory board also have a large light channel so that the light from the LEDs can reach the bottom of the glass bottle. All three stages fit within an aluminum shell housing with appropriate holes for power and switches.

We also worked with an external industrial design team comprised of undergraduates Sarah Spalding, Jill Moore, Lucas Mai, and Jarek Diaz. They produced several concept drawings, 3D models, as well as a physical wood base prototype shown in Figure 14 Appendix C.

2.4 Printed Circuit Board (PCB)

We chose to design a single PCB to minimize the required space for electronics in the lava lamp base. Further, our PCB is designed to be 4" diameter circle and have mounting holes for mounting in the base.

We designed our PCB following the the ECE Electronics Services Shop design rules and guidelines [8], making sure to use appropriately wide traces, and keep vias and top side traces to components to a minimum. We used through-hole components to make the assembly and testing of the board easier. The finished PCB layout is in Figure 2, and the assembled boards are in Figure 39 and Figure 40 located in Appendix G.

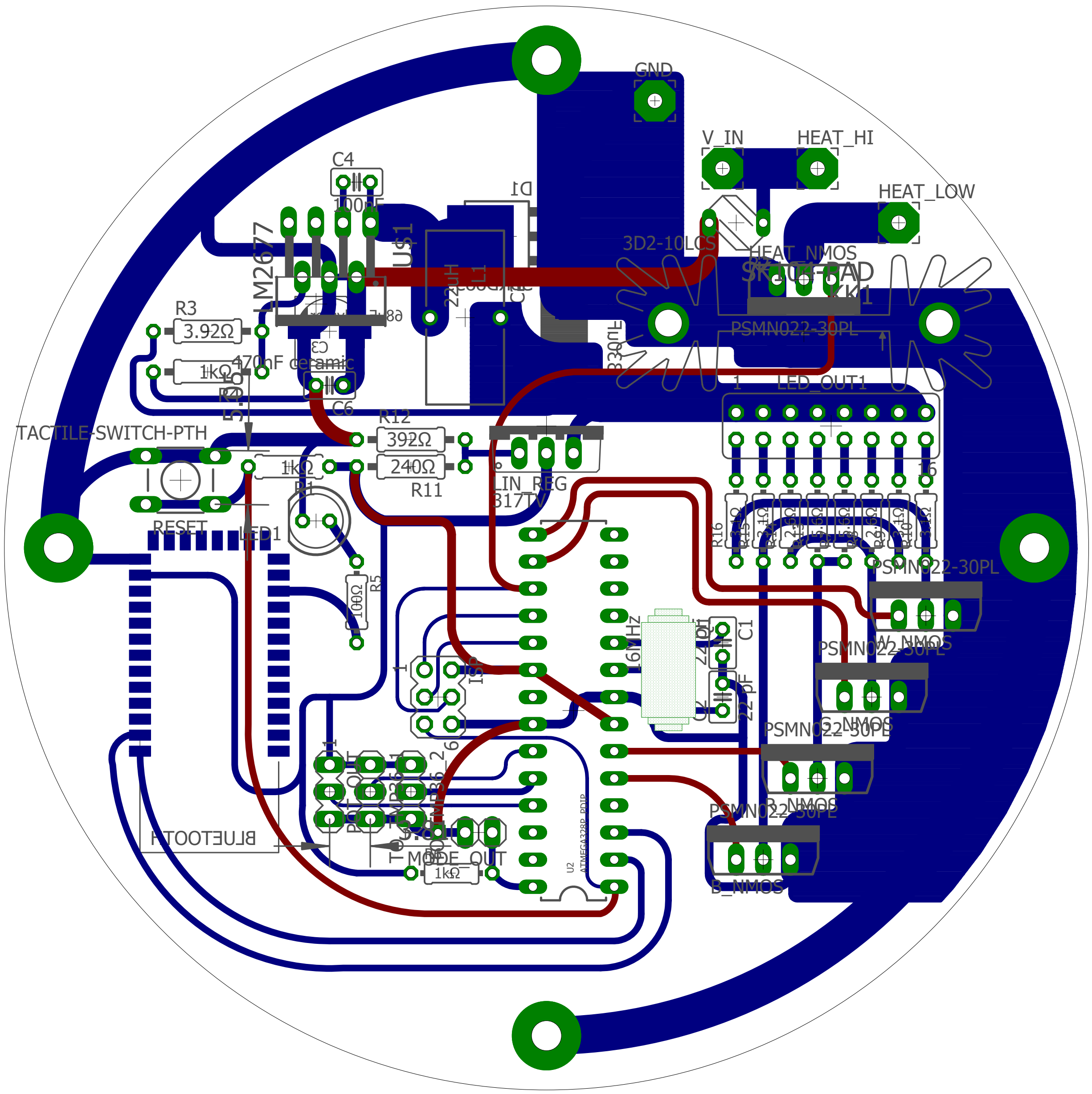


Figure 2: PCB design in EagleCAD, combining components from power, input, lighting, and microcontroller modules.

3 Software Design

In Figure 22 Appendix D we can see the flow diagram for the software that will be running on the MCU. Just like our hardware design, the software design is split up into independent modules for light and heat. Additionally, there is a one time initialization step that sets all of the variables and pin configurations.

3.1 Lighting Control

During the “Read User Input” sub-block from Figure 22 Appendix D, the state of the button is determined to be either pressed or not pressed. we sense the state of the dimmer switch as a real number between zero and one.

In the “Calculate LED PWM Signals” sub-block, we use user input to determine what LED PWM value to send out. In Figure 23 Appendix D, we display the color finite state machine (FSM). The input “B” to the FSM is true only for a rising edge of the button press. When this occurs, the mode toggles to the next color and stays there until the next rising edge. This toggling feature can keep circling back to allow the user to select any color they want. Red, green, blue, purple, and aqua are implemented. However, since we have four color channels (Red, Green, Blue, and White) that we can control independently to a high degree of precision, we are able to essentially produce any color. Once the color is selected, the intensity is controlled by the dimmer switch value by multiplying the selected PWM values by the dimmer value.

In the “Set LED PWM Signals” sub-block, the PWM values are sent out from the MCU to the n-channel MOSFETs to control the current flowing through the LEDs. Consequently, the LEDs light up with the user-indicated color and intensity.

3.2 Temperature Control

The “Heat” section from Figure 22 Appendix D starts by reading in temperature sensor data from the temperature sensors in the “Read Temperature Sensors” sub-block. The first sensor measures the temperature of our heat source and acts as a safety feature. The second sensor measures the temperature of the surface of the lava lamp glass. This surface temperature is the temperature that we are interested in controlling.

The “Calculate Heat Heat PWM Signals” sub-block encompasses the majority of the software design. We designed and implemented a proportional controller. The controller computes the difference between the desired lava lamp temperature and the sensed temperature. It then multiplies this error by a selected gain value to obtain the input. The following sections will go into more detail of the control.

Finally, in the “Set Heat PWM Signals” sub-block, after converting the input to a duty cycle out of 100 while considering the PWM resolution, a PWM value is computed. Then, the MCU sends out this PWM signal to the transistors that control the current flowing through our heat resistors, thus heating up our system.

3.3 System Model

A traditional lava lamp can take up to two hours to warm up and has a total recommended operation time of around eight hours. Due to this fact, exhaustive experiments of our system are impractical and simulation becomes crucial. In order to simulate our system we first need to create a model and derive the relevant system equations.

We model our system as a cylindrical lava lamp and a cylindrical heat source as seen in Figure 24 Appendix D. To simplify our control of the system, we will consider each block in Figure 24 Appendix D (Lava Lamp, Heat Source, and Air) as having a uniform internal temperature T_{Lava}, T_{Heat}, and T_{Air} respectively. We also model the heat flow between blocks using Equation 8 [9].

$$q = \frac{1}{R}(T_1 - T_2), \tag{8}$$

Where,

q is the heat energy flow $(\frac{J}{sec})$

R is the thermal resistance $(\frac{^\circ C sec}{J})$

T is the temperature $(^\circ C)$

And the net heat-energy flow into a substance affects the temperature of the substance according to the relation in Equation 9 [9].

$$\dot{T} = \frac{1}{C}q \tag{9}$$

Where,

C is the thermal capacity $(\frac{J}{^\circ C})$

q is the sum of heat flows obeying Equation 8

and $\dot{T}$ is the rate of change of the temperature $(\frac{^\circ C}{sec})$

Using Equation 8, Equation 9, and our model we derive the differential equations that determine the temperature in each block of Figure 24 Appendix D. Note, that we will consider the Air block to have an infinite thermal capacity, allowing it to exchange heat without changing its temperature.

In Figure 25 Appendix D the heat flow between every surface is defined. A positive heat flow will indicate the flow of thermal energy from the base of the arrow to the tip. The definitions are as follows:

q_1: From the heat source to the lava lamp

q_2: From the heat source to the air (side of cylinder)

q_3: From the heat source to the air (bottom of cylinder)

q_4: From the power resistor to the heat source

q_5: From the lava lamp (top of cylinder) to the air

q_6: From the lava lamp (side of cylinder) to the air

Therefore,

$$q_{Heat} = q_4 - q_1 - q_2 - q_3 \tag{10}$$

$$q_{Lava} = q_1 - q_5 - q_6 \tag{11}$$

We assign a thermal resistance R_i to each of the q_i and plug them in to Equation 8. We exclude q_4 which we assume we control directly. Then, we obtain the net heat flows by evaluating Equation 10 and Equation 11. Finally, we plug in the net heat flows in to Equation 9 to obtain the following:

$$\dot{\tilde{T}}_{Heat} = (\frac{-1}{R_{1,2,3}C_{Heat}})\tilde{T}_{Heat} + (\frac{1}{R_1 C_{Heat}})\tilde{T}_{Lava} + (\frac{1}{C_{Heat}})q \tag{12}$$

$$\dot{\tilde{T}}_{Lava} = (\frac{1}{R_1 C_{Lava}})\tilde{T}_{Heat} + (\frac{-1}{R_{1,5,6}C_{Lava}})\tilde{T}_{Lava} \tag{13}$$

Where

$$R_{1,2,3} = \frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3}, \frac{R_1 R_5 R_6}{R_1 R_5 + R_1 R_6 + R_5 R_6}, q = q_4$$

$$\tilde{T}_{Heat} = T_{Heat} - T_{Air}, \text{ and } \tilde{T}_{Lava} = T_{Lava} - T_{Air}$$

3.4 Controller Design and Simulation

From the previous section we have the differential equations that govern our system. By making some calculations from the physical properties of our real system, we can determine parameter values as seen in Appendix E. We transform this into a state space representation for easier analysis of the form seen in Equation 14.

$$\dot{x} = Ax + Bu \tag{14}$$

For our system we have:

$$\begin{bmatrix} \dot{\tilde{T}}_{Heat} \\ \dot{\tilde{T}}_{Lava} \end{bmatrix} = \begin{bmatrix} (\frac{-1}{R_{1,2,3}C_{Heat}}) & (\frac{1}{R_1 C_{Heat}}) \\ (\frac{1}{R_1 C_{Lava}}) & (\frac{-1}{R_{1,5,6}C_{Lava}}) \end{bmatrix} \begin{bmatrix} \tilde{T}_{Heat} \\ \tilde{T}_{Lava} \end{bmatrix} + \begin{bmatrix} \frac{1}{C_{Heat}} \\ 0 \end{bmatrix} q \tag{15}$$

The system matrix, A, contains information about the stability of the system. The eigenvalues of this matrix are the poles in the complex plane. If these poles are all in the left hand plane (real part less than 0), then we can say our system is stable. For our system, the eigenvalues, and thus poles, are:

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} -0.00142001 \\ -0.0000045667 \end{bmatrix} \tag{16}$$

Therefore, we can say that the open-loop system is stable. Also, from the state space representation we can obtain the system block diagram as seen in Figure 26 Appendix D. The constants are:

$$C_1 = (\frac{1}{C_{Heat}}), C_2 = (\frac{1}{R_{1,2,3}C_{Heat}}), C_3 = (\frac{1}{R_1 C_{Lava}}), C_4 = (\frac{1}{R_{1,5,6}C_{Lava}}), C_5 = (\frac{1}{R_1 C_{Heat}})$$

A traditional lava lamp would at this point give a constant control input to the system and perform open-loop control. Figure 27 Appendix D shows the results from our Simulink simulation. The input power was chosen to reflect two common power levels for lava lamp light bulbs (25 W and 40 W) as well as 64 W.

Although the parameters may not be completely accurate and our model is not perfect, we see the intrinsic problem with this control scheme. Using a large input power allows the system to get to the operating temperature faster. Consequently, it also causes the system to reach dangerous levels faster. Using a small input power would get to the dangerous levels slower, but it would also get to the operating temperature at a much reduced rate.

We propose a simple proportional feedback controller that addresses both of these problems. In Figure 28 Appendix D, we see the new block diagram with an error and gain added. Simulating our new controller, we see the effects of having different gains.

Figure 29 Appendix presents the results of this simulation. The first thing to notice is that as K increases the amount of damping decreases. Ideally, the system is critically damped and there is no overshoot. When K is 20, it appears to be very close to this. The second thing to see is the steady state error in the previous plot. The values for the errors are listed in Table 4 Appendix D. As K increases the error decreases. So, to design our controller there is a trade-off between steady state error and overshoot.

Figure 30 Appendix D illustrates the control effort which is the amount of power provided to the heating source. Because it is impossible for our system to input a negative heat, we see the controller flat-line at zero for the over-shot values. Based on these plots we decided to assign the theoretical value as $K = 20$.

However, the specific parameters of our real system are most likely different and difficult to accurately measure. This results in a different optimal K. After experimenting we selected a K of 100.

4 Verification

4.1 Power Supply

To verify our power supply, we drew the required DC loads and measured the voltages. Figures 32 and 33 are oscilloscope captures of this verification. We met all verification parameters according to our requirements and verification table (see appendix A). However, we had some significant high frequency noise on the 3.3 V rail for the MCU and temperature sensors. They have wide input voltage tolerance, 2.7 V to 5.5 V [3][10], thus we set our 3.3 V range to be at least 2.8 V, and up to 3.4 V.

However, since reading the temperature sensors requires an analog voltage reading, if accuracy is to be considered, they impose an additional requirement missing from our requirements table that the 3.3 V supply not be noisy. In order to achieve the stated ±2°C accuracy, there cannot be high frequency noise with peak-to-peak voltage higher than 0.020 V. Our prototype had much higher noise than this, with peak-to-peak voltages of up to 0.4 V at the 22 MHz range. While we were able to have stable thermal control with use of aggressive digital averaging filters, lowering this noise would be a much more robust solution to noise issues in our temperature readings. Figure 34 shows the raw sensor data.

4.2 Light Source

Unfortunately our lava lamp did not outperform the traditional lava lamp in terms of raw light output. A traditional lava lamp outputs 12.54 lux when measured according to the procedure in the Requirements and Verification table, but our lava lamp only produced approximately 7 lux.

However, we did meet our brightness control requirement with an incremental capability of 0.04 lux. Moreover, we verified the color requirements by observing the color changes on the final version of the lava lamp.

4.3 Heat Source

We wanted our heat source to be able to handle temperatures of at least 90°C for extended periods of time. We decided on this temperature after some experiments using our heat source to heat up regular lava lamps. This requirement was verified actually verified during these experiments. Some data samples for the heat source adjustment requirement are displayed in Figure 35 and Figure 36 Appendix F. Our smallest measured heat increment was 0.01 W which easily meets the requirement.

4.4 Temperature Sensor

Our temperature sensors are analog so there was little worry about temperature reading speed. However, we confirmed the reading speed while monitoring the MCU serial output which was updated at a rate of 100 Hz. The sensor accuracy was confirmed by both the data sheet and independent tests with a infrared heat gun. Data for this test is shown in Table 5 Appendix F.

4.5 MCU

The native capabilities of the ATmega328P met all of our requirements.

4.6 Buttons and Switches

The requirements for this modules were all verified on the final version of the lava lamp. Button presses successfully changed the color and the slider successfully adjusted the brightness of the LEDs.

4.7 Control

We achieved all our control requirements. Figure 37 Appendix F is a plot of the MCU serial reported data for a warm up from from room temperature to a 40°C lamp temperature. This figure is the verification of all of our control requirements. Additional verification material can be found in video form on the ECE445 website within our project.

Our rise time, the time it takes until the lava globules move for the first time (Figure 38 Appendix F), is 11.5 minutes (16.5 minutes minus a 5 minute offset). This condition is indicated by the vertical red dashed line. The offset time is from our lava lamp starting five minutes after our testing system began.

The overshoot value, or the value above our desired temperature is much less than 10°C. As seen in Figure 37 Appendix F, it rises up to almost 41°C but never higher.

Finally, the steady state error requirement is just barely met. Displayed on Figure 37 Appendix F are the horizontal black dashed lines at 41°C and 39°C. In order for our system to meet this requirement, the lava lamp temperature must be between these lines at steady-state because our controller is set to 40°C.

5 Conclusions

5.1 Accomplishments

Our primary goal for this project was to make the lava lamp heat up and start functioning faster than a traditional lava lamp. By implementing a heating element that can dissipate 100 W of power as heat and carefully linking it to the glass by a metal heat spreader and thermal compound we were able to cut the start up time by more than half.

We sought to decouple the lighting and heating mechanism to allow independent temperature and light control. This was achieved by creating a resistor heating array that is distinct and separate from the LED lighting array. The temperature of our lamp can be adjusted without affecting the color or brightness of the LEDs and vice-versa.

Finally, we achieved our goal of providing long term temperature control. We are able to set predefined temperatures that the MCU can maintain for several hours (we have tested up to nine hours) and possibly indefinitely.

5.2 Areas for Improvement

Unfortunately, although the LEDs that we selected are very bright, we were unable to meet our goal of emitting more light than a traditional lava lamp. This was mostly due to an oversight on part selection when we made our requirement table. To solve this problem we could either add more color LEDs or add additional higher power white LEDs. We could also change the mechanical design of the base to place the LEDs closer to the glass bottle or experiment with LEDs configurations that illuminate outwards instead of exclusively upwards.

We could also improve the layout of the PCB. All of the components work, but wiring the PCB was especially difficult when carried out within the small confines of the base's shell. In the future we would like to move the LED headers further from the large heat sink. We would also like to do a new layout of the PCB to reduce the area of current loops which contribute to some of the noise problems we experienced.

5.3 Safety and Ethical Considerations

The safety issues of our device are primarily electrical, chemical, and thermal in nature. We minimized the risk for electric shock by using heat shrink on any exposed wire. We also used high current wire-to-wire connectors for any wire junctions so there are no exposed wires. Regardless, the potential risk is still present and the user should be informed according to the IEEE Code of Ethics regarding informing the public of hazards [11].

The chemical hazard stems from using possibly unsafe materials inside of the glass bottle lamp. This risk could only manifest itself in the event that the user attempts to ingest the glass bottle contents. We used a lamp from a modern commercial lava lamp, so if a leak occurs the materials should be able to be cleaned up like any common household spill as long as the contents are not too hot.

Thermal burns are the most significant and likely safety issue. The outside of the glass bottle reaches a temperature of approximately 40°C / 104°F which is warm to the touch but will not cause any burns. The internal contents of the glass bottle reach around 65°C / 150°F These temperatures are enough to cause contact burns within a second of contact [12] if the user somehow comes in contact with them. The heating element itself will reach a temperature of 97°C / 207°F which is extremely dangerous to touch. It is hard to physically access the heating element when the base is fully assembled, but the user will still be warned of this hazard.

Aside from properly warning the user of safety hazards there really aren't any other ethical issues in the development of the use of the lava lamp.

5.4 Future Directions

Although we experienced a fair amount of success in meeting our requirements, there is still much that can be done to improve the lava lamp. One example is to continue pursuing an industrial design model such as those shown in Figures 15, 16, 17, 18, 19, 20, and 21. This is extremely important when considering taking a unique product like this to the consumer market. It will definitely be more expensive than a traditional lava lamp so having a special look or feel will give the product an edge.

Another path we want to pursue is the subject of heat transfer. Our heat resistors were limited because they could only be heated to less than 100°C because our wires will begin to melt at higher temperatures. The higher temperatures also impose other heat safety issues. However, we believe that inductive heating is a very promising prospect. We would like to investigate the concept of a coil on the base that transmits power to another coil inside the lava lamp to produce heat internally.

Additional future features could include LEDs placed in a ring around base for better lighting, wireless capability with a mobile companion application, improved PCB layout for ease with assembly, more accurate and less noisy sensors, or even an auto-calibration feature to determine system parameters and air temperature for more accurate and advanced control schemes.

6 Cost and Schedule

6.1 Cost Analysis

Table 1: Personnel portion of project costs

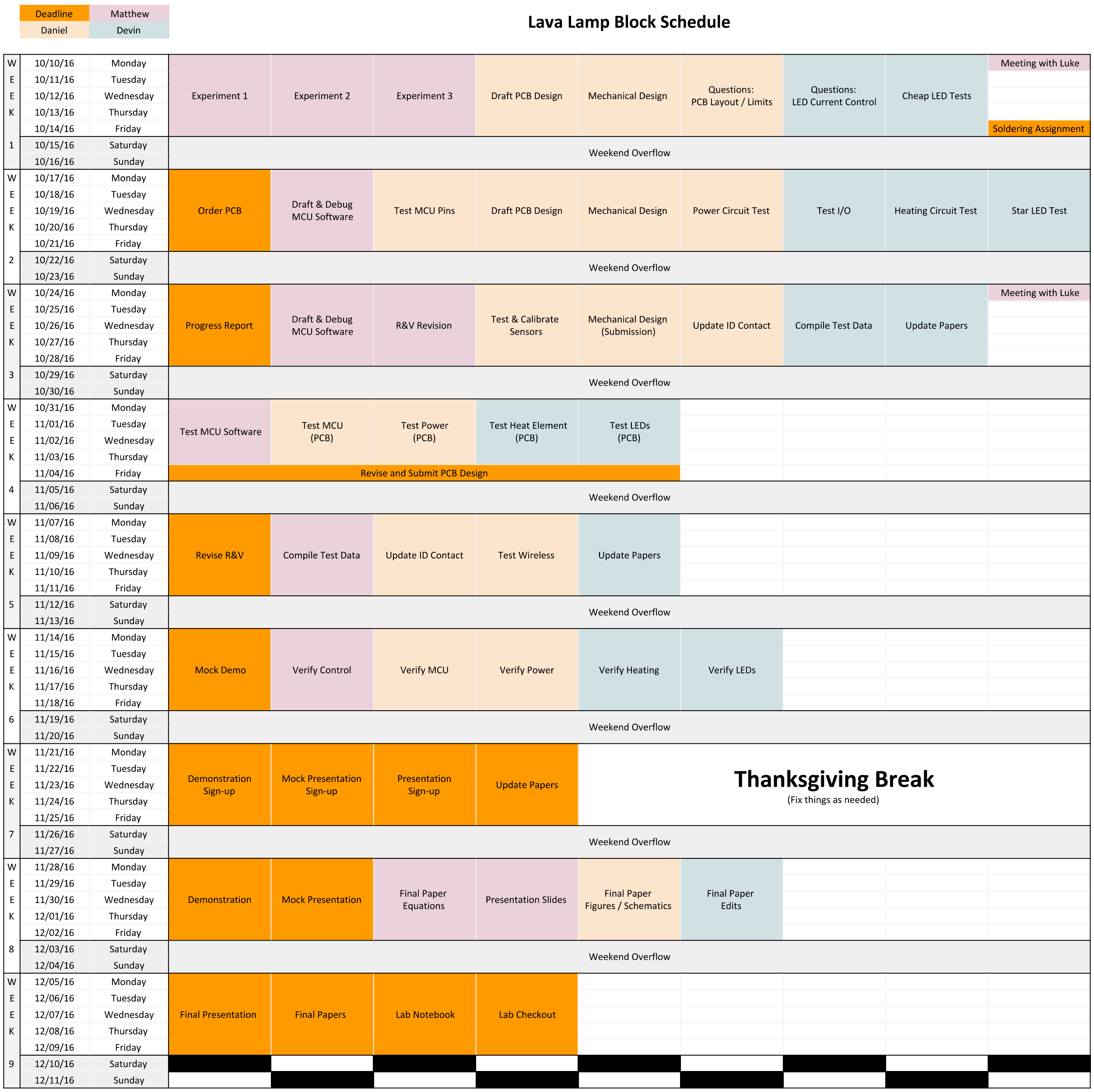
Personnel	
Average Starting Salary	$67,000 [13]
Per Hour Rate	$32
Total Hours (20 / Week)	280
Personnel Cost (3 members)	$27,056
Total Labor Cost (including overhead)	**$67,641**

Table 2: List of parts for our project with associated unit costs, amounts, and grand total

Parts				
Function	**Part**	**Amt.**	**Unit Price**	**Total Price**
Power Supply	AC $\rightarrow$ 20V, 6.75A with Power Plug	1	$13.95	$13.95
Linear regulator	LM317	1	$0.53	$0.53
Switching regulator	LM2677	1	$5.96	$5.96
Mode Switch	Tactile Button	1	$0.89	$0.89
Sliding Potentiometer	RS30111A602N	1	$2.85	$2.85
Kill Switch	PRASA1-16F-BB0BW	1	$0.93	$0.93
Heating Resistors	HS25 16R F	4	$2.77	$11.08
LED	CREE XLamp XM-L Color LED	2	$15.29	$30.58
NMOS Transistor	PSMN022-30PL	5	$0.58	$2.90
Temperature Sensor	TMP36	2	$2.27	$4.54
Microcontroller	ATmega328P	1	$2.00	$2.00
Testing	Lava Lamp	1	$29.99	$29.99
Bluetooth Chip	HC-06	1	$4.00	$4.00
Thermal Adhesive	Arctic Alumina Thermal Adhesive 5g	1	$7.77	$7.77
Oscillator	FOXSLF/160-20	1	$0.33	$0.33
Total Parts Cost				**$118.30**

6.2 Schedule Summary

We had four schedules this semester and each served a different purpose. Figure 3 is a graphical version of the schedule that was useful for quick glances.



Lava Lamp Block Schedule

Deadline	Matthew
Daniel	Devin

W	10/10/16	Monday	Experiment 1	Experiment 2	Experiment 3	Draft PCB Design	Mechanical Design	Questions: PCB Layout / Limits	Questions: LED Current Control	Cheap LED Tests	Meeting with Luke
E	10/11/16	Tuesday									
E	10/12/16	Wednesday									
K	10/13/16	Thursday									
	10/14/16	Friday									Soldering Assignment
1	10/15/16	Saturday	Weekend Overflow								
	10/16/16	Sunday									
W	10/17/16	Monday	Order PCB	Draft & Debug MCU Software	Test MCU Pins	Draft PCB Design	Mechanical Design	Power Circuit Test	Test I/O	Heating Circuit Test	Star LED Test
E	10/18/16	Tuesday									
E	10/19/16	Wednesday									
K	10/20/16	Thursday									
	10/21/16	Friday									
2	10/22/16	Saturday	Weekend Overflow								
	10/23/16	Sunday									
W	10/24/16	Monday	Progress Report	Draft & Debug MCU Software	R&V Revision	Test & Calibrate Sensors	Mechanical Design (Submission)	Update ID Contact	Compile Test Data	Update Papers	Meeting with Luke
E	10/25/16	Tuesday									
E	10/26/16	Wednesday									
K	10/27/16	Thursday									
	10/28/16	Friday									
3	10/29/16	Saturday	Weekend Overflow								
	10/30/16	Sunday									
W	10/31/16	Monday	Test MCU Software	Test MCU (PCB)	Test Power (PCB)	Test Heat Element (PCB)	Test LEDs (PCB)				
E	11/01/16	Tuesday									
E	11/02/16	Wednesday									
K	11/03/16	Thursday									
	11/04/16	Friday	Revise and Submit PCB Design								
4	11/05/16	Saturday	Weekend Overflow								
	11/06/16	Sunday									
W	11/07/16	Monday	Revise R&V	Compile Test Data	Update ID Contact	Test Wireless	Update Papers				
E	11/08/16	Tuesday									
E	11/09/16	Wednesday									
K	11/10/16	Thursday									
	11/11/16	Friday									
5	11/12/16	Saturday	Weekend Overflow								
	11/13/16	Sunday									
W	11/14/16	Monday	Mock Demo	Verify Control	Verify MCU	Verify Power	Verify Heating	Verify LEDs			
E	11/15/16	Tuesday									
E	11/16/16	Wednesday									
K	11/17/16	Thursday									
	11/18/16	Friday									
6	11/19/16	Saturday	Weekend Overflow								
	11/20/16	Sunday									
W	11/21/16	Monday	Demonstration Sign-up	Mock Presentation Sign-up	Presentation Sign-up	Update Papers	Thanksgiving Break (Fix things as needed)				
E	11/22/16	Tuesday									
E	11/23/16	Wednesday									
K	11/24/16	Thursday									
	11/25/16	Friday									
7	11/26/16	Saturday	Weekend Overflow								
	11/27/16	Sunday									
W	11/28/16	Monday	Demonstration	Mock Presentation	Final Paper Equations	Presentation Slides	Final Paper Figures / Schematics	Final Paper Edits			
E	11/29/16	Tuesday									
E	11/30/16	Wednesday									
K	12/01/16	Thursday									
	12/02/16	Friday									
8	12/03/16	Saturday	Weekend Overflow								
	12/04/16	Sunday									
W	12/05/16	Monday	Final Presentation	Final Papers	Lab Notebook	Lab Checkout					
E	12/06/16	Tuesday									
E	12/07/16	Wednesday									
K	12/08/16	Thursday									
	12/09/16	Friday									
9	12/10/16	Saturday									
	12/11/16	Sunday									

Figure 3: An example of one of the schedules we used this semester. We call this one the graphical schedule.

7 References

[1] Smithsonian Magazine. (2016). The History of the Lava Lamp, [Online]. Available: http://www.smithsonianmag.com/arts-culture/the-history-of-the-lava-lamp-21201966/.

[2] CREE. (2016). CREE XLamp XM-L Color LEDs Datasheet, [Online]. Available: http://www.cree.com/~/media/Files/Cree/LED-Components-and-Modules/XLamp/Data-and-Binning/XLampXML_Color.pdf.

[3] Analog Devices. (2016). TMP35/TMP36/TMP37 Datasheet, [Online]. Available: http://www.analog.com/media/en/technical-documentation/data-sheets/TMP35_36_37.pdf.

[4] Lumen Coalition. (2016). Lumens vs Watts, [Online]. Available: http://lumennow.org/lumens-vs-watts/.

[5] Texas Instruments. (2016). LM2677 Datasheet, [Online]. Available: http://www.ti.com/lit/ds/symlink/lm2677.pdf.

[6] ——, (2016). LM317 Datasheet, [Online]. Available: http://www.ti.com/lit/ds/symlink/lm317.pdf.

[7] NXP. (2016). PSMN022-30PL Datasheet, [Online]. Available: http://www.nxp.com/documents/data_sheet/PSMN022-30PL.pdf.

[8] University of Illinois - ECE Electronics Services Shop. (2016). Design Requirements For Our Milled PCBs, [Online]. Available: http://eshop.ece.illinois.edu/pcbdesign/designreq/designreq.php.

[9] G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems*, 6th ed. 2011, pp. 50–51.

[10] Atmel. (2015). ATmega48A/PA/88A/PA/168A/PA/328/P DATASHEET, [Online]. Available: http://www.atmel.com/images/Atmel-8271-8-bit-AVR-Microcontroller-ATmega48A-48PA-88A-88PA-168A-168PA-328-328P_datasheet_Complete.pdf.

[11] IEEE. (2016). 7.8 IEEE Code of Ethics, [Online]. Available: http://www.ieee.org/about/corporate/governance/p7-8.html.

[12] Burn Foundation. (2016). Safety Facts on Scald Burns, [Online]. Available: http://www.burnfoundation.org/programs/resource.cfm?c=1&a=3.

[13] University of Illinois at Urbana Champaign. (2016). ECE Graduate Starting Salaries, [Online]. Available: https://www.ece.illinois.edu/admissions/why-ece/salary-averages.asp.

Appendix A Requirements and Verification Table

Table 3: Requirements and Verification Table

Requirements	**Verification**
Power Supply 1. Provide 5A between 19-20V at max power. (4 points) 2. Provide at least 3A between 5.5-6.2V at max power. (8 points) 3. Provide at least 500mA at 2.8 - 3.4V. (8 points)	*Power Supply* 1. (a) Set a the HP 6060B Electronic load machine to be a current sink of 5A. (b) Connect the load to the PCB (green and red jack). (c) Connect power converter (laptop charger) to the power jack. (d) Plug power converter into a wall outlet. (e) Connect voltmeter probes to the 20V terminals on the PCB. (f) Turn on the power to the PCB using power the switch. (g) Voltmeter should read between 19-20V. 2. (a) Set a the HP 6060B Electronic load machine to be a current sink of 3A. (b) Connect the load to the PCB (green and red jack). (c) Connect power converter (laptop charger) to the power jack. (d) Plug power converter into a wall outlet. (e) Connect voltmeter probes to the 6V terminals on the PCB. (f) Turn on the power to the PCB using power switch. (g) Voltmeter should read at between 5.5-6.2V. 3. (a) Set a the HP 6060B Electronic load machine to be a current sink of 500mA. (b) Connect the load to the PCB (green and red jack). (c) Connect power converter (laptop charger) to the power jack. (d) Plug power converter into a wall outlet. (e) Connect voltmeter probes to the 3.3V terminals on the PCB. (f) Turn on the power to the PCB using power switch. (g) Voltmeter should read at between 2.8-3.4V.

<table>
<tr>
<td>

Light Source

1. Must produce at least 10 lux of light from 1cm +- 1cm distance away. (6 points)
2. Must be able to control brightness in increments of 0.05 +- 0.03 lux or less. (6 points)
3. Provide red, green, blue, purple, and aqua lighting. (6 points)

</td>
<td>

Light Source

1. (a) Ensure that the LED is on and at max power with the sliding potentiometer switch.
   (b) Turn on the PYLE PLMT12 light meter.
   (c) Press the range button three times.
   (d) Place the light meter halfway between the bottom and top of the glass.
   (e) Orient the light so that it is facing towards the bottom middle of the lamp and touching the glass.
   (f) Record the value.
2. (a) Create a program that can sweep across the microcontrollers 256 possible duty cycles.
   (b) Ensure the LED is on.
   (c) Turn on the PYLE PLMT12 light meter.
   (d) Press the range button three times.
   (e) Place the light meter halfway between the bottom and top of the glass.
   (f) Orient the light so that it is facing towards the bottom middle of the lamp and touching the glass.
   (g) Record the value.
   (h) Press the mode button to move to next duty cycle value.
   (i) Repeat recording and cycling until satisfied.
3. (a) Ensure the LED is on.
   (b) Press the mode button to cycle through the various colors.
   (c) Detect the color difference visually or by using a color sensor.

</td>
</tr>
</table>

<table>
<tr><td>

Heat Source

1. Must be able to sustain a temperature of at least 90°C for at least 30 minutes.
2. Must be able to have power adjusted in increments as small as 1W. (10 points)

</td><td>

Heat Source

1. (a) Connect heating resistor network to lab bench power supply capable of high power output.
   (b) Turn on the lab bench power supply.
   (c) Set the voltage to 15V.
   (d) Allow the temperature to rise to 90°C.
   (e) Adjust the voltage to keep the temperature at 90°C as needed.
   (f) Maintain 90°C for 30 minutes.
2. (a) Create a program that can sweep across the microcontrollers 256 possible duty cycles.
   (b) Connect heat source to PCB using the heating jack. These wires must also connect to a multimeter.
   (c) Measure the resistance of the heating network. It should be 4Ω.
   (d) Switch multimeter to voltage reading.
   (e) Ensure PCB is connected to power and turn it on.
   (f) Record voltage at duty cycle setting 0.
   (g) Press the mode button to move to next duty cycle value.
   (h) Repeat recording and cycling until satisfied.
   (i) Use Equation 5 to calculate power. Calculate differences between each setting.

</td></tr>
<tr><td>

Temperature Sensor

1. Able to read temperature at least once every second. (0 points)
2. Accuracy within two degrees Celsius. (0 points)

</td><td>

Temperature Sensor

1. (a) Attach the temperature sensor to an object at room temperature.
   (b) Use Arduino or Beaglebone software to take measurements faster than once a second.
2. (a) Check data sheets.

</td></tr>
</table>

<table>
<tr>
<td>
MCU

Needs at three analog and and two digital input channels. (0 points)
Needs at least five PWM and one digital output channels. (0 points)
Needs at least 20kB of memory. (0 points)
Needs a clock of at least 20 MHz. (0 points)
Needs to be able to run on 5V±1V. (0 points)

</td>
<td>
MCU

(a) Verify with the datasheet.
(a) Verify with the datasheet.
(a) Verify with the datasheet.
(a) Hook up the clock pin to the oscilloscope positive terminal and ground to the ground terminal
(b) Measure the clock frequency
(a) Verify with the datasheet

</td>
</tr>
<tr>
<td>
Buttons and Switches

Able to accept user input from the mode button and transmit the correct state. (1 point)
Able to accept user input from the sliding potentiometer and transmit the correct state. (1 point)

</td>
<td>
Buttons and Switches

(a) Turn on the PCB.
(b) Ensure LEDs are on.
(c) Press the mode switch button.
(d) Verify that system moves to the correct state.
(a) Turn on the PCB.
(b) Ensure LEDs are on.
(c) Use the sliding potentiometer switch.
(d) Verify that the LEDs change brightness.

</td>
</tr>
</table>

Control 1. Overshoot of T_{Lava} of less than $10°C$ above the desired temperature when starting from the air temperature (which is in the range of $20°C$ to $27°C$). (15 points) 2. Rise time of 40 minutes for T_{Lava} (from an Air temperature of between $20°C$ and $27°C$ to a temperature in which the lava globules are moving). (15 points) 3. Steady State Error of Less than 1.0 $°C$ between the desired T_{Lava} and the sensor readings (at an Air temperature of between $20°C$ and $27°C$). (10 points)	*Control* 1. (a) Measure the air temperature to make sure it is in the range between $20°C$ and $27°C$. If not, adjust the temperature and repeat this step. (b) Connect to the debugging port of the system and read the desired temperature and system temperature from the sensor. (c) Start the controller and watch the sensor reading to see if it is ever $10°C$ above the desired temperature. Do this for 8 hours or until T_{Lava} stays within a 1.0 $°C$ window for 10 minutes, whichever comes first. (d) If the above condition never occurs it passes the criterion. 2. (a) Measure the air temperature to make sure it is in the range between $20°C$ and $27°C$. If not. adjust the temperature and repeat this step. (b) Start the controller and begin a stopwatch. (c) Wait until the wax globules begin moving. Stop the stopwatch. (d) If the time reads 40 minutes or less the requirement is met. 3. (a) Measure the air temperature to make sure it is in the range between $20°C$ and $27°C$. If not, adjust the temperature and repeat this step. (b) Connect to the debugging port of the system and read the desired temperature and system temperature from the sensor. (c) Start the controller and wait until the system reaches a steady state as indicated by simply waiting for 8 hours or until T_{Lava} stays within a 1.0 $°C$ window for 10 minutes, whichever comes first. (d) Then, measure the difference between the desired temperature and sensor reading for T_{Lava}. If this difference is less than 1.0 it passes the criterion.

Appendix B Circuit Schematic Figures

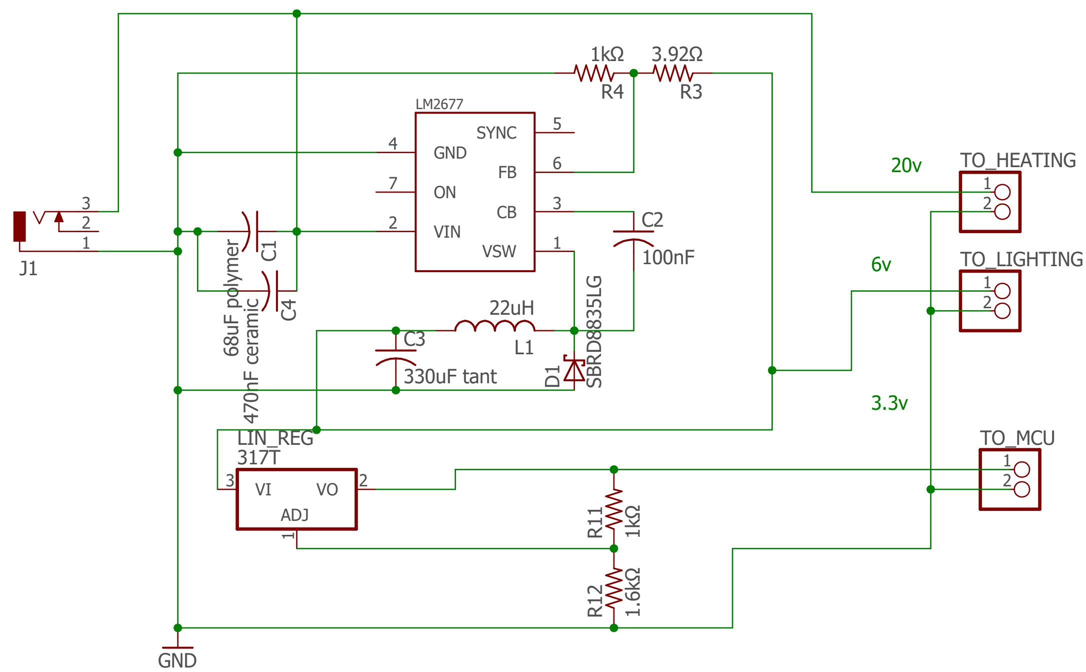


Figure 4: Circuit schematic of the power board. An LM2677 buck converter regulates a 6 V power supply for the lighting module and linear regulator. The LM317 linear regular regulates the 6 V to a 3.3 V supply for the MCU. The sync and on inputs to the converter are intentionally left floating.

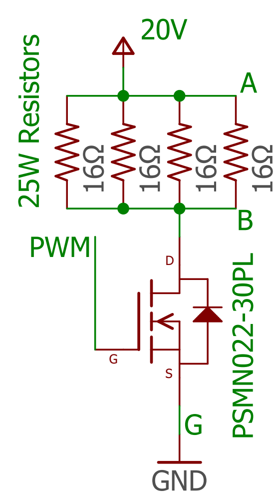


Figure 5: Circuit schematic of the heating element. Points A and G are test points for checking the voltage and resistance across the entire array. Points A and B are used for testing the same characteristics over individual resistors.

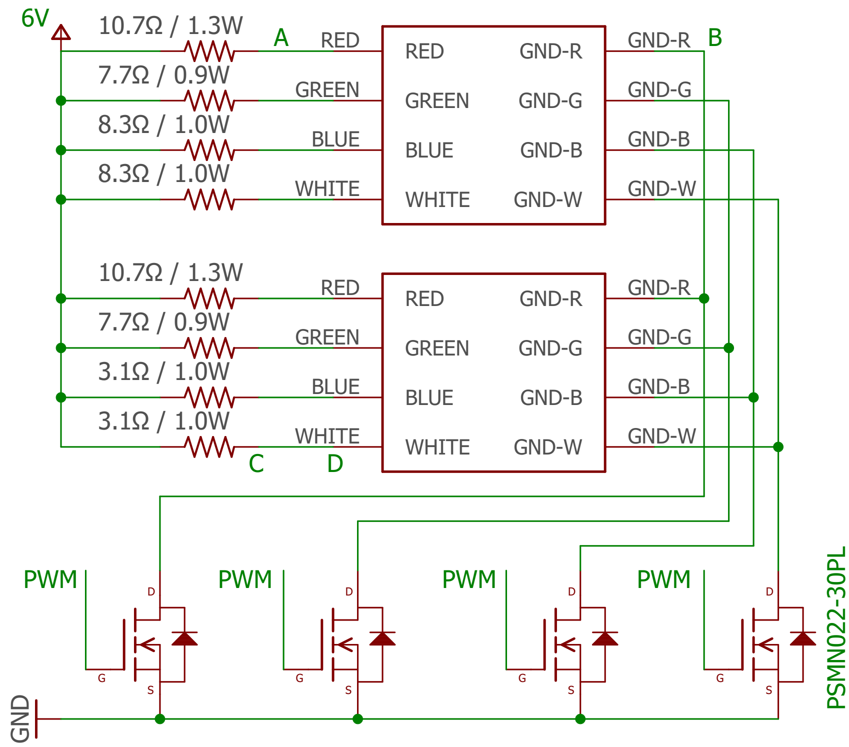


Figure 6: Circuit schematic of the LED circuit. The RGBW n-channel MOSFET chips control the respective RGBW channels for the two LEDs by utilizing the PWM functionality of the MCU. Each color channel has a current protection resistor. Points A and B illustrate the test points for checking the voltage across the LEDs.

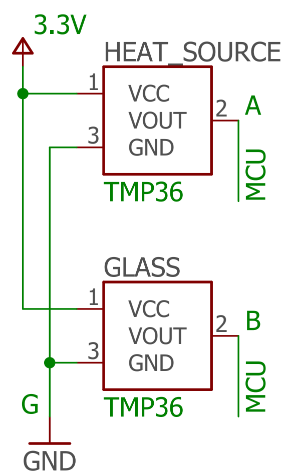


Figure 7: Circuit schematic of the temperature sensor module. One TMP36 is thermally epoxied to the heat source and the other is thermally epoxied to the the glass container. Points A, B, and G illustrate the test points for testing the output voltages. These voltages are sent to the MCU for use in the temperature control feedback loop.

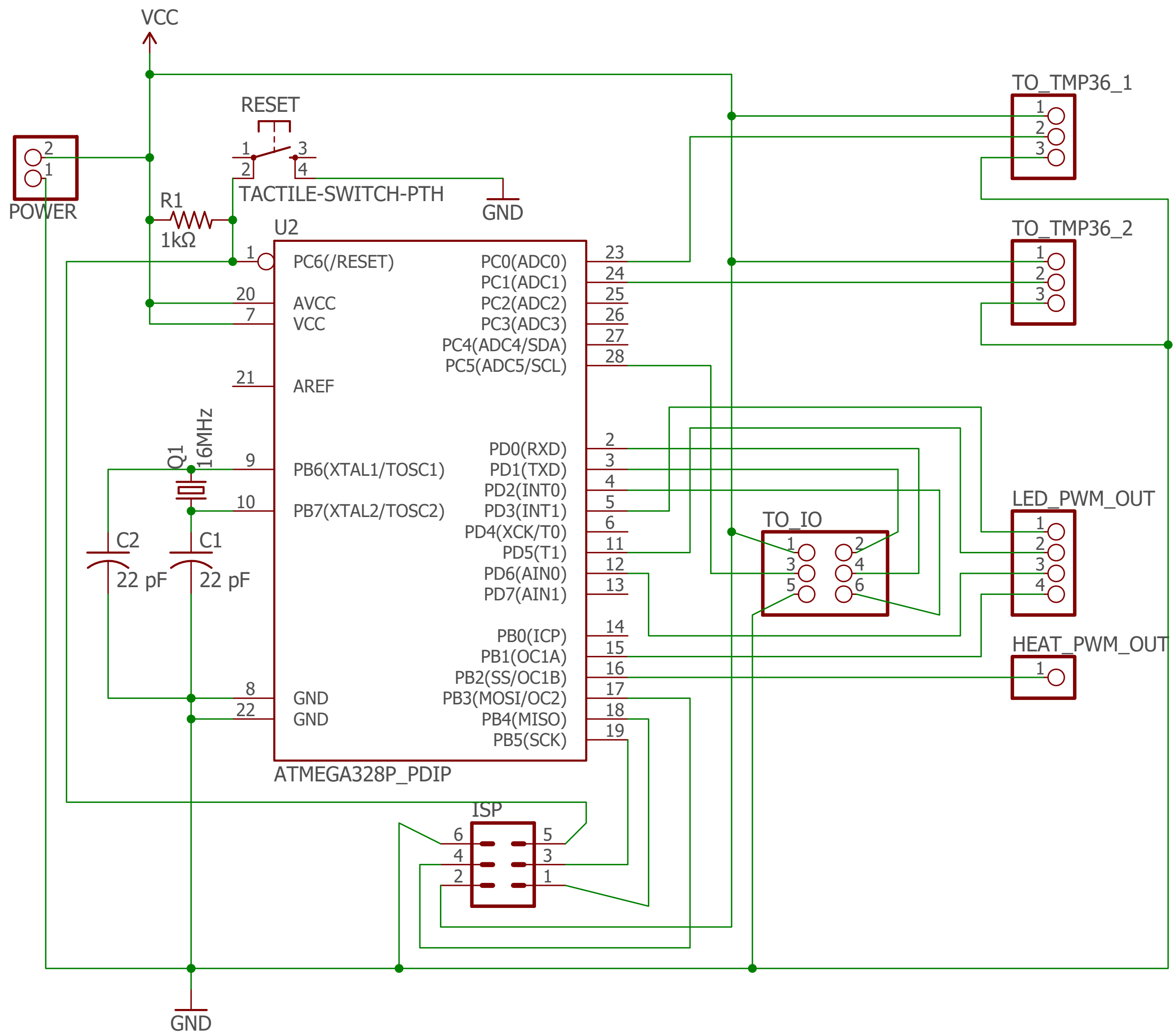


Figure 8: Circuit schematic of the MCU. The primary component is the ATmega328P, which controls the logic of the lamp. Five of the six available PWM outputs are in use to drive the LED channels and the heating element. An ISP header and reset button are made accessible for programming. Headers for connections to other boards are also present.

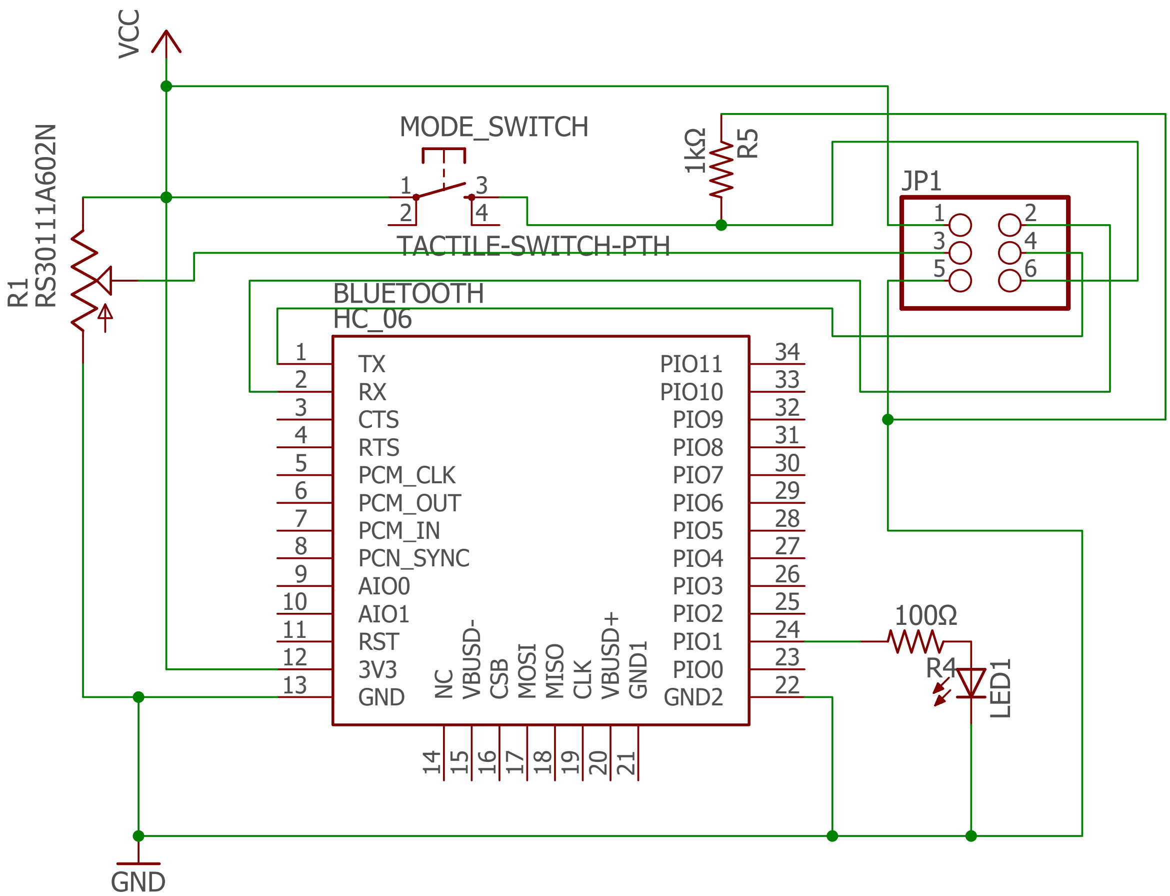


Figure 9: Circuit schematic of the I/O board. This board contains a tactile switch and sliding potentiometer which are externally accessible through cut-outs in the lamp housing. It also contains the HC_06 module, which allows a bluetooth host to connect to the lamp and issue serial commands to the MCU (future). The board has one header for connection to the MCU board, which supplies it with power, reads the switch state, reads the potentiometer voltage, and communicates with the HC_06 via serial communication.

Appendix C Lava Lamp Base Figures

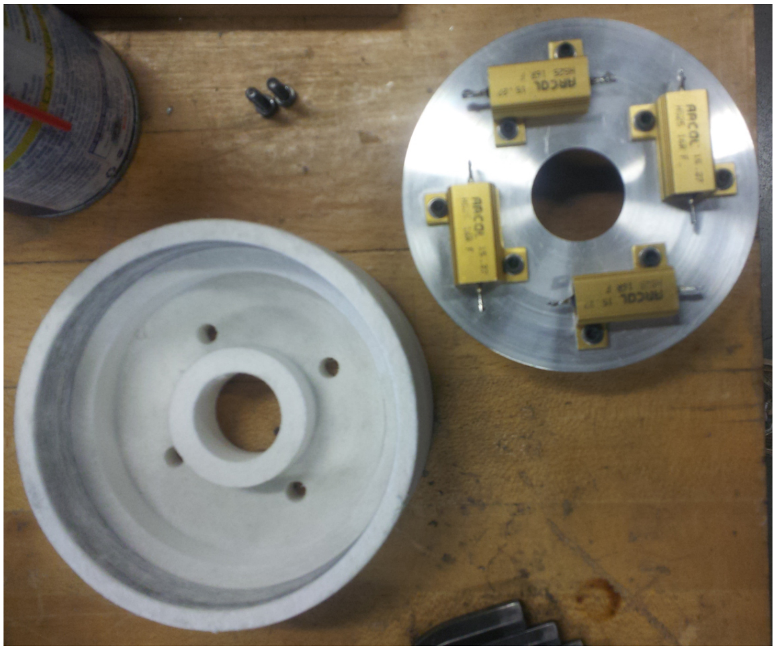


Figure 10: (Left) Refractory board thermal housing. (Right) The underside of the aluminum heat spreading cup with heating resistors attached. The circular hole in the middle is used to channel light from the LEDs to the bottom fo the glass bottle.

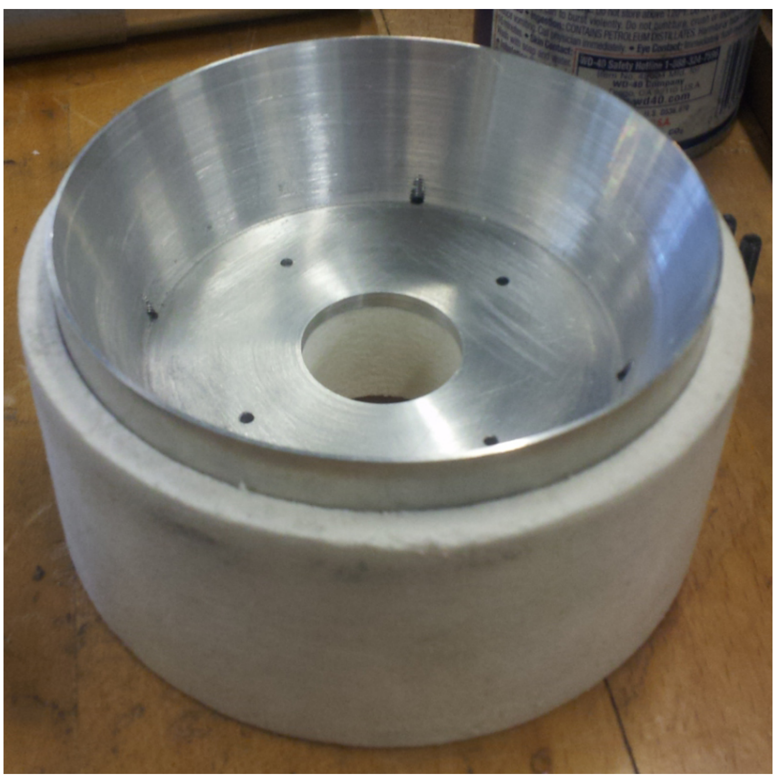


Figure 11: Heat spreader sitting within the thermal housing. Note the internal light channel is also insulated.

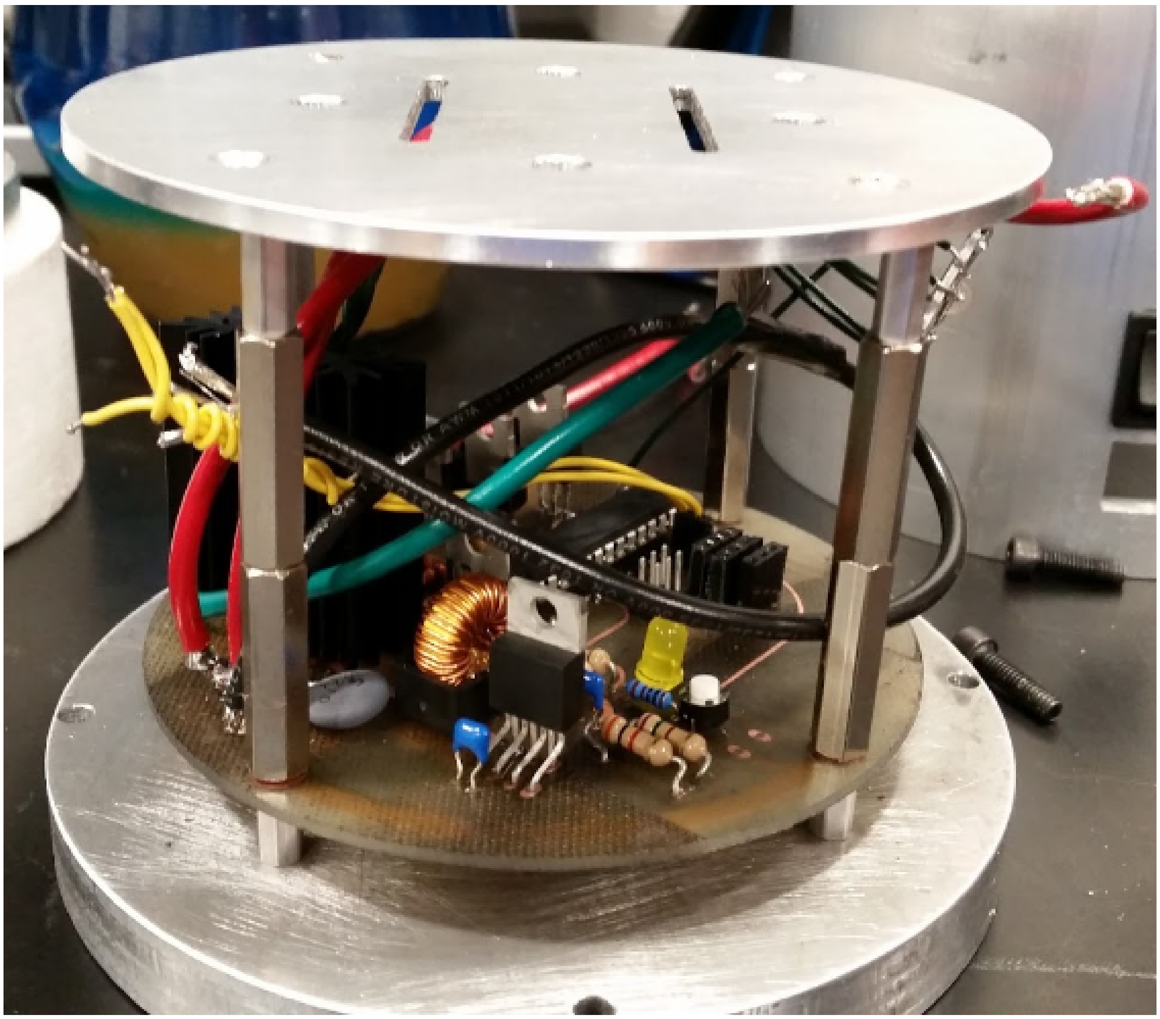


Figure 12: Core structure of the PCB housing. The PCB is mounted to a base plate and the LED plate is held above via vertical standoffs. The bottom of the thermal insulation cup sits flush with the LED plate.

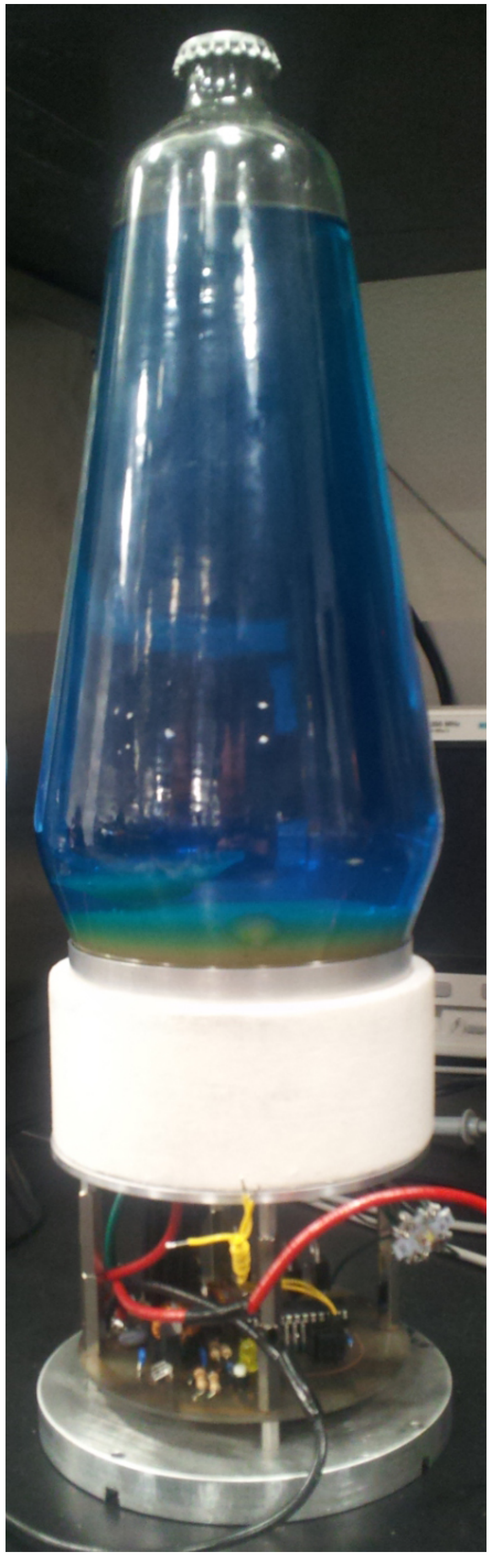


Figure 13: Complete internal assembly of the base (with lava lamp).

Figure 14: Wood base created for us by the Industrial Design team.

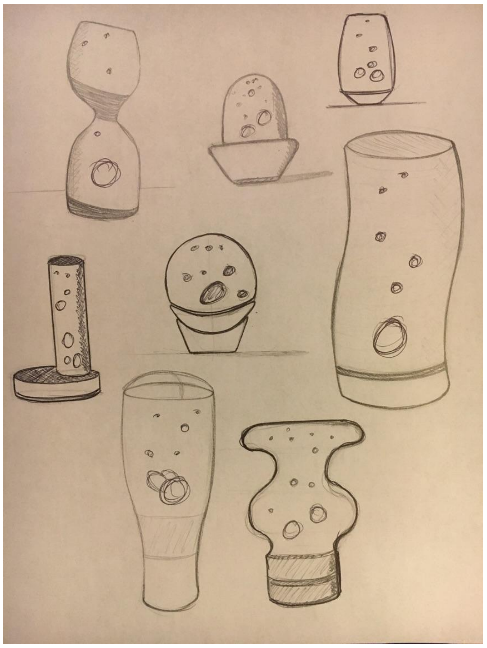


Figure 15: Rough sketch of future lava lamp designs made by our industrial design student collaborators.

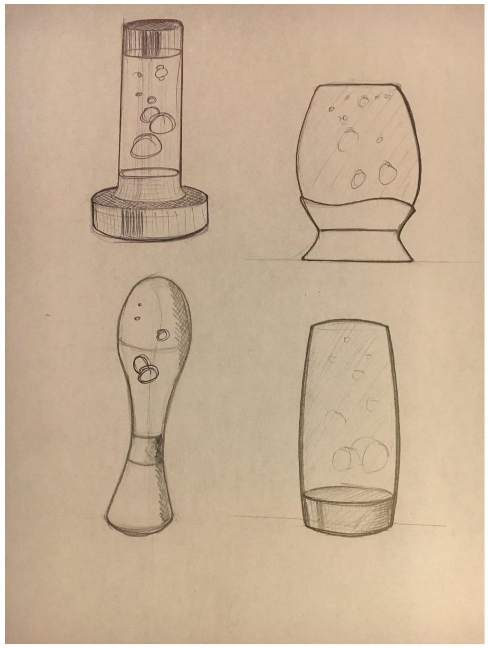


Figure 16: Rough sketch of future lava lamp designs made by our industrial design student collaborators.

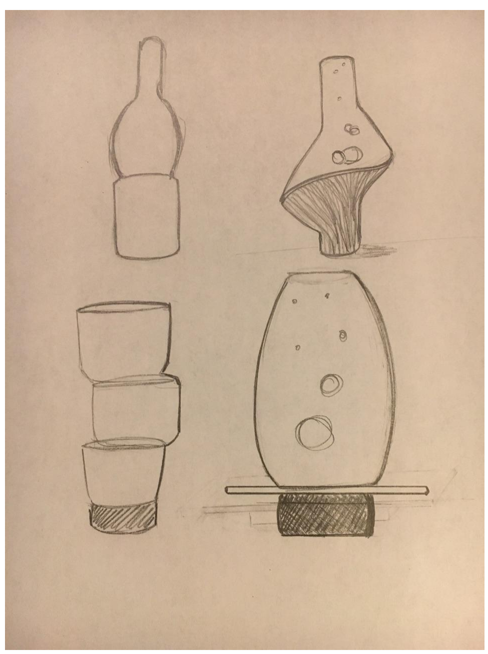


Figure 17: Rough sketch of future lava lamp designs made by our industrial design student collaborators.

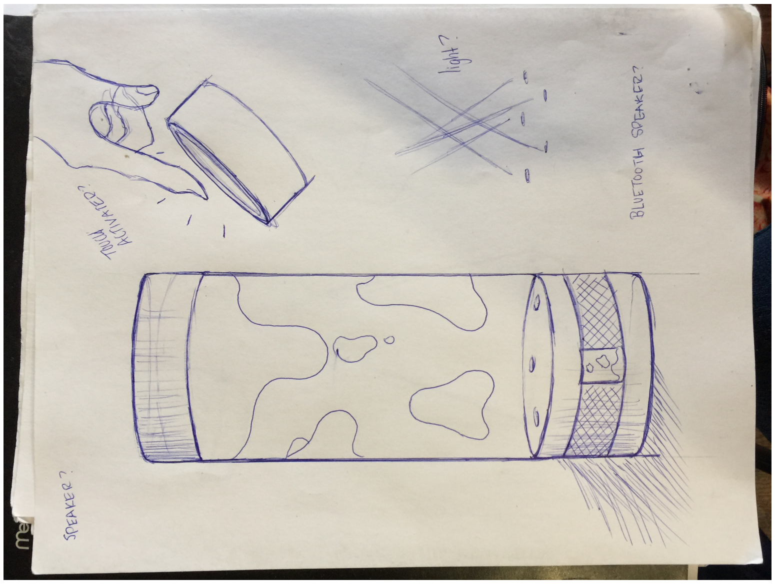


Figure 18: Rough sketch of future lava lamp designs made by our industrial design student collaborators.

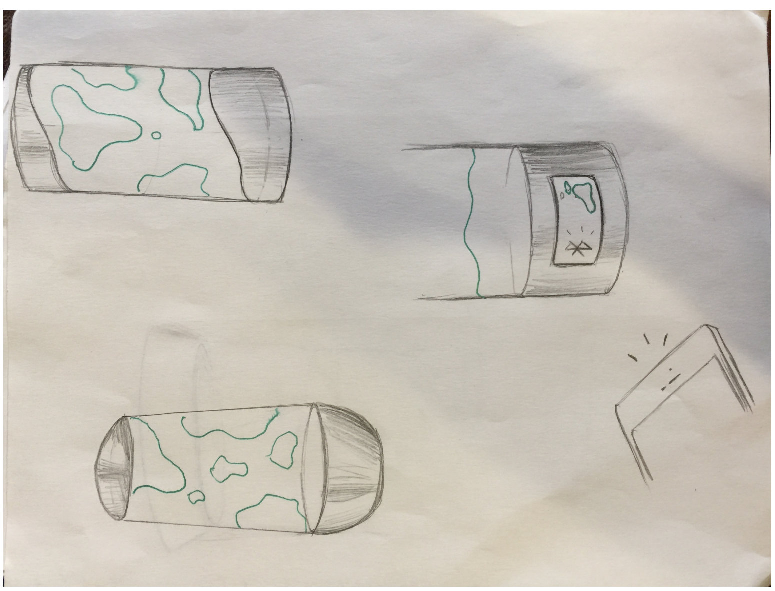


Figure 19: Rough sketch of future lava lamp designs made by our industrial design student collaborators.

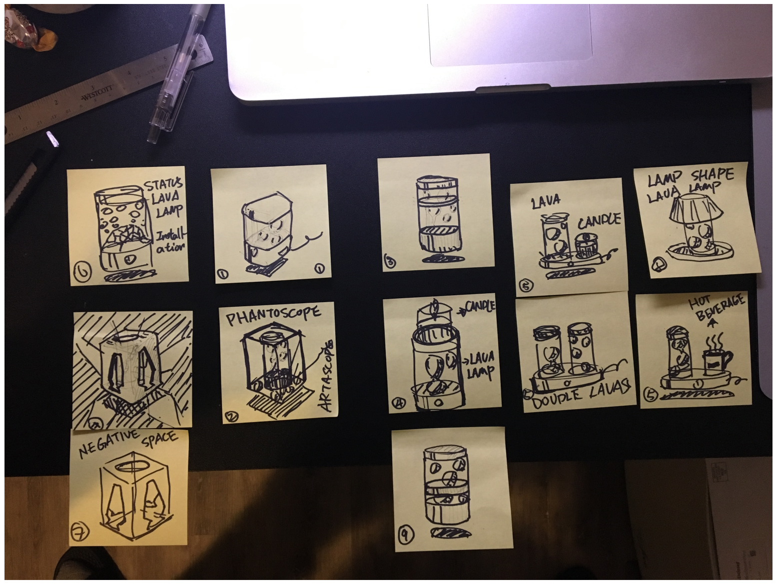


Figure 20: Rough sketch of future lava lamp designs made by our industrial design student collaborators.

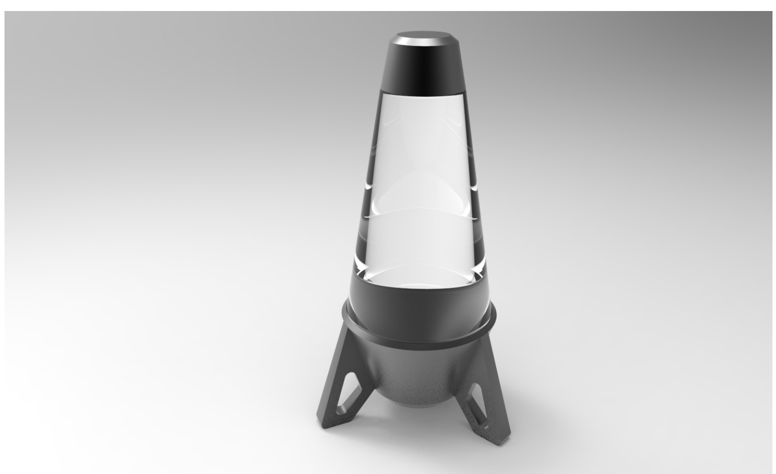


Figure 21: CAD .model of a future lava lamp "Rocket Ship" design made by our industrial design student collaborators

Appendix D Software Design Figures

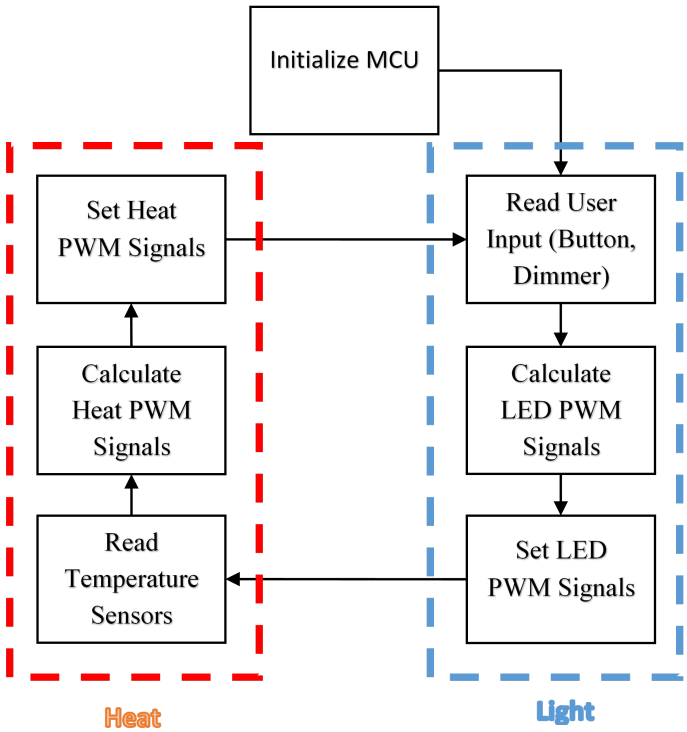


Figure 22: MCU software flow diagram

Table 4: Simulated steady state error for various gains using controller

K	Steady State Error ($°C$)
10	0.5592
20	0.2816
50	0.1131
100	0.0566

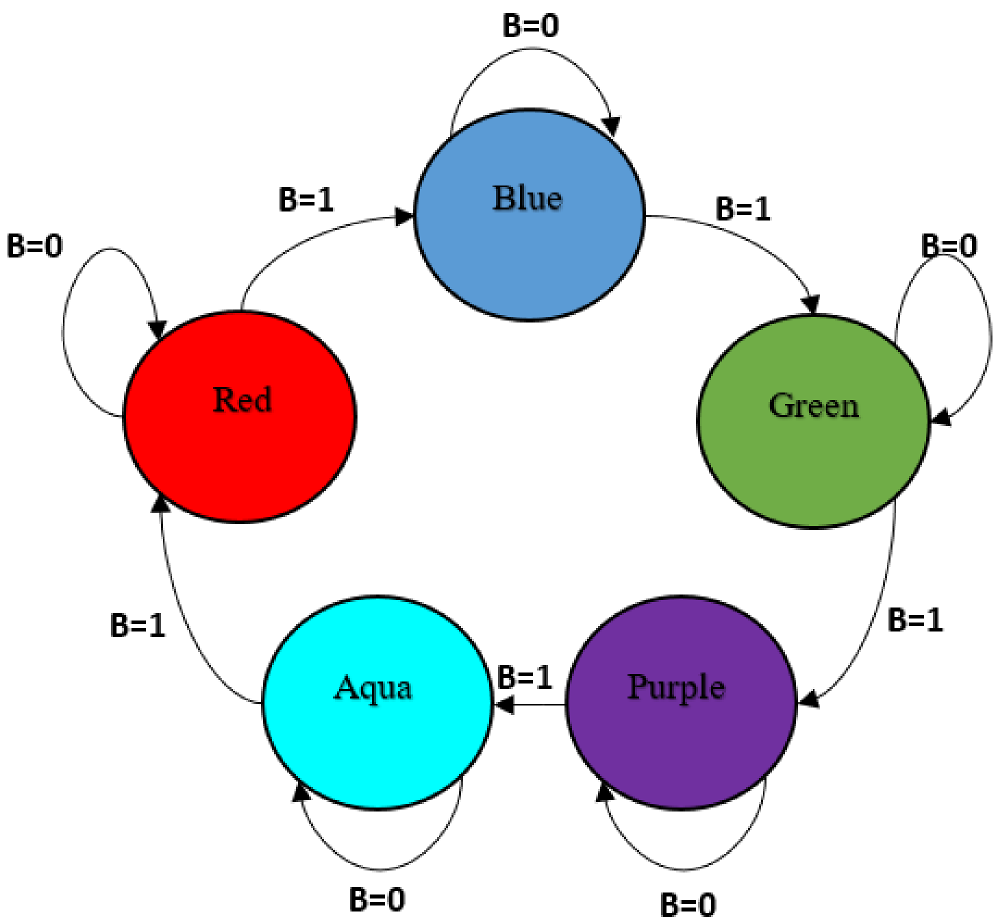


Figure 23: Color finite state machine

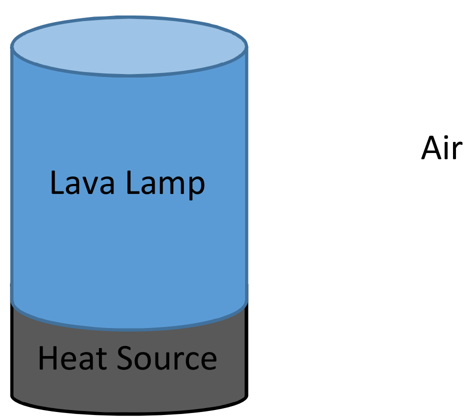


Figure 24: Physical model of lava lamp system as two cylinders

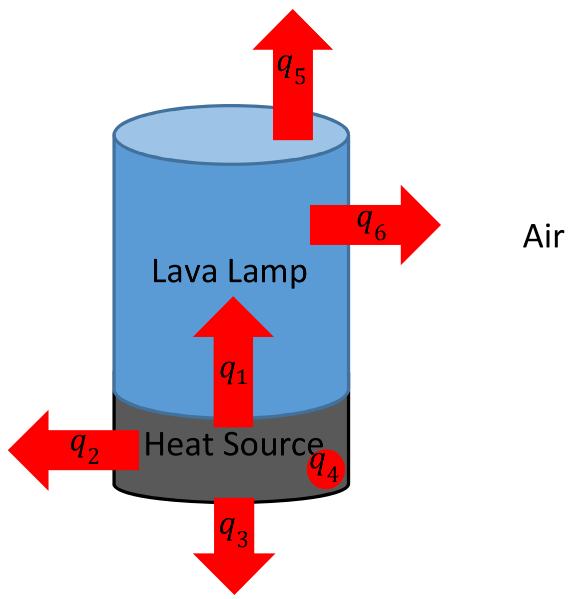


Figure 25: Heat flow illustrated on lava lamp system model

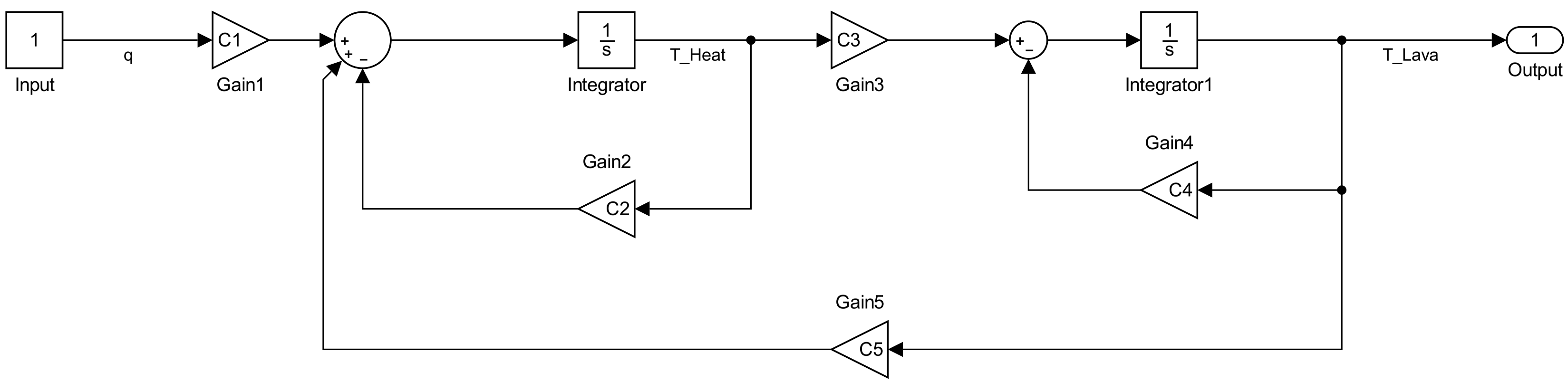


Figure 26: Lava lamp control system block diagram

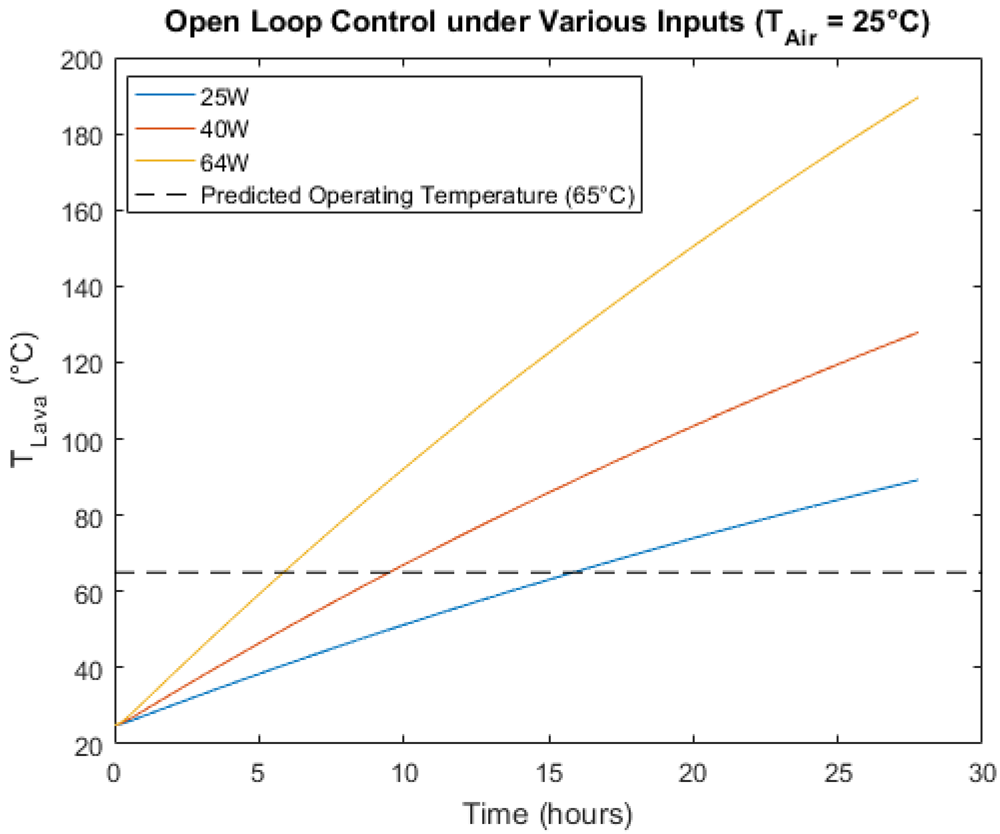


Figure 27: Open loop control under various inputs. Temperature of lava lamp vs. Time is plotted.

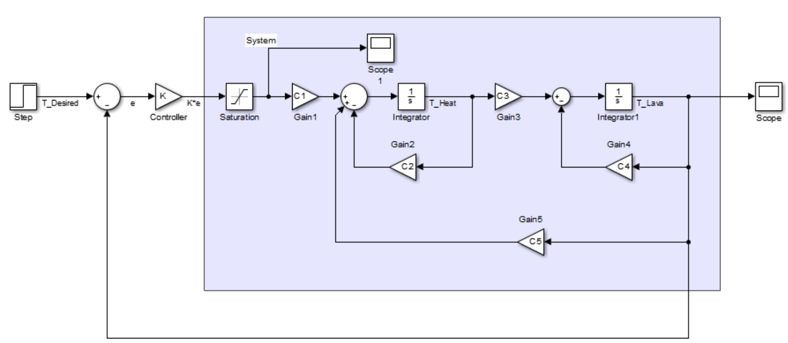


Figure 28: Proportional control Laplace domain system model block diagram

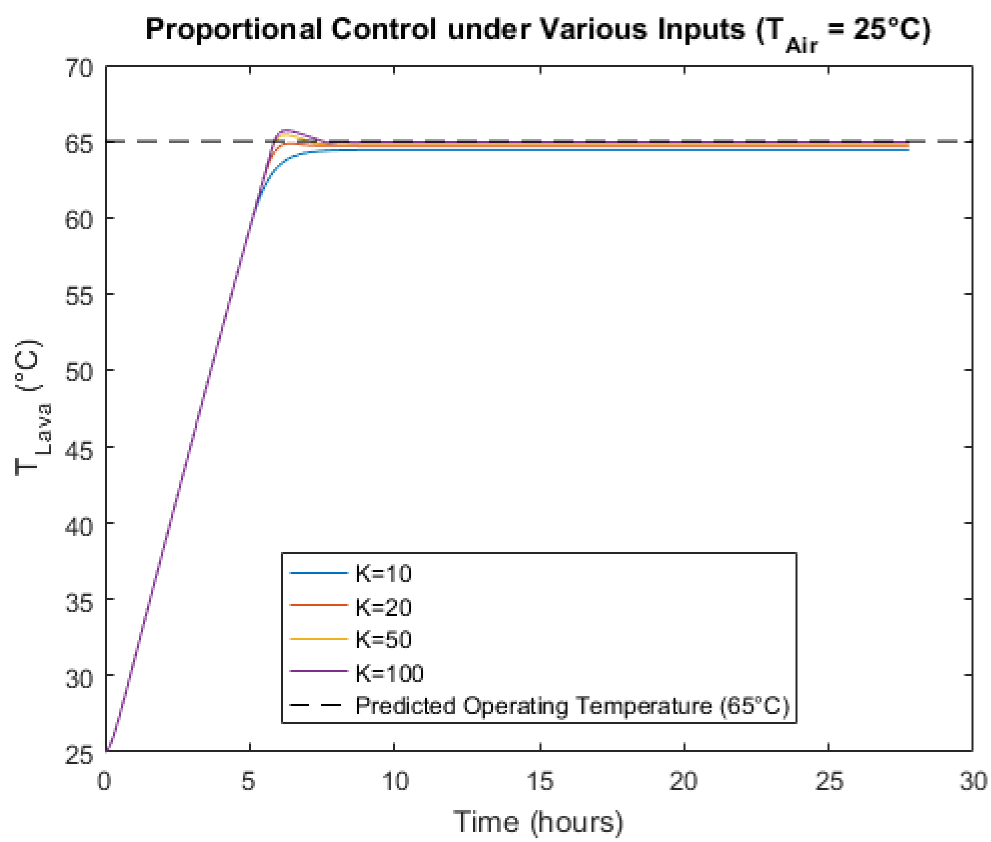


Figure 29: Proportional control under various gains. Temperature of the lava lamp vs. Time is plotted.

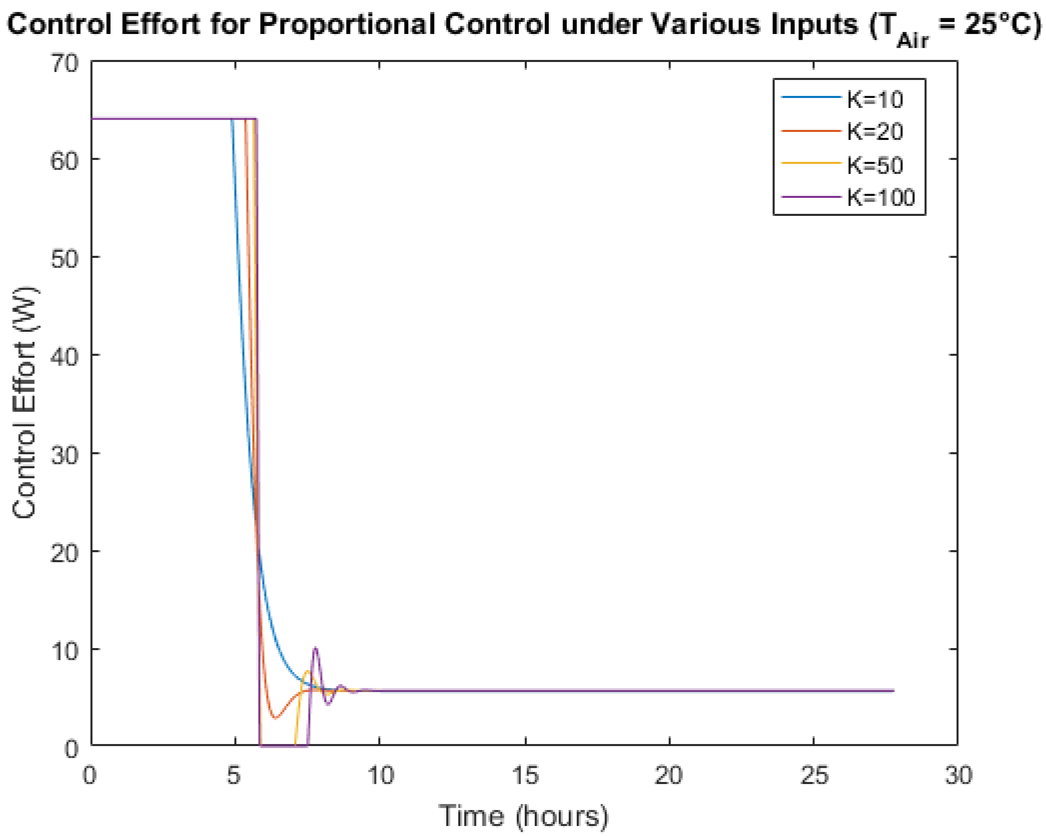


Figure 30: Control effort for proportional control under various gains

Appendix E Theoretical Estimation of System Parameters

In order to simulate our model, we must first estimate the parameters of our model. Namely, we must estimate:

$$R_1, R_2, R_3, R_4, R_5, C_{Heat}, \text{ and } C_{Lava}$$

In our formulation of thermal resistance from Equation 8, we never specified the method of heat transfer between our system blocks. We merely gave a constant of proportionality and assumed that the majority of the change in temperature would happen at the surfaces. At this point it will be useful to extend our model by specifying dimensions. As we can see in Figure 31, the dimensions of the lava lamp cylinder are (height H and diameter D), and of the heat source cylinder (height h).

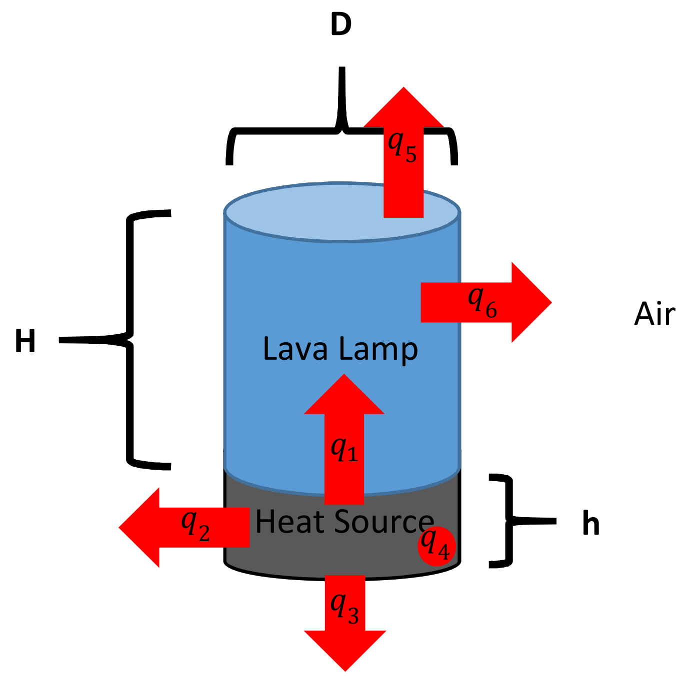


Figure 31: Heat flow illustrated on model with dimensions specified

For the lava lamp and heat sources we have chosen the values as:

$$H = 0.69 \text{ m}, D = 0.115 \text{ m}, \text{ and } h = 0.03 \text{ m}$$

To estimate these parameters, we must now consider what method of heat transfer is dominant and derive the thermal resistance from the appropriate equations. Through some derivation we can obtain a theoretical estimate for the parameters. We assume R_1 is dominantly conduction and the other thermal resistances are dominantly convection. Beyond that, the method to obtain these parameters are out of the scope of this document. The values we obtained are below.

$$R_1 = 0.9628 \; (\frac{K}{W})$$

$$R_2 = 184.5 \; (\frac{K}{W})$$

$$R_3 = 192.6 \; (\frac{K}{W})$$

$$R_5 = 192.6 \; (\frac{K}{W})$$

$$R_6 = 8.022 \; (\frac{K}{W})$$

$$C_{Lava} = 29,990 \; (\frac{J}{^\circ C})$$

$$C_{Heat} = 757.2 \; (\frac{J}{^\circ C})$$

Appendix F Verification Figures

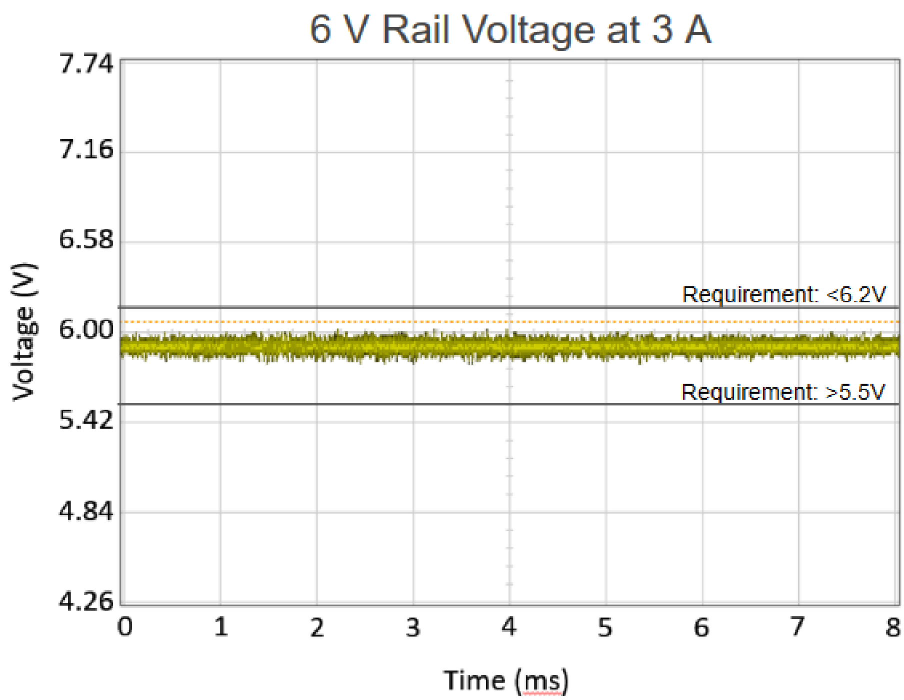


Figure 32: Oscilloscope reading of the 6 V power rail supplying 3 A.

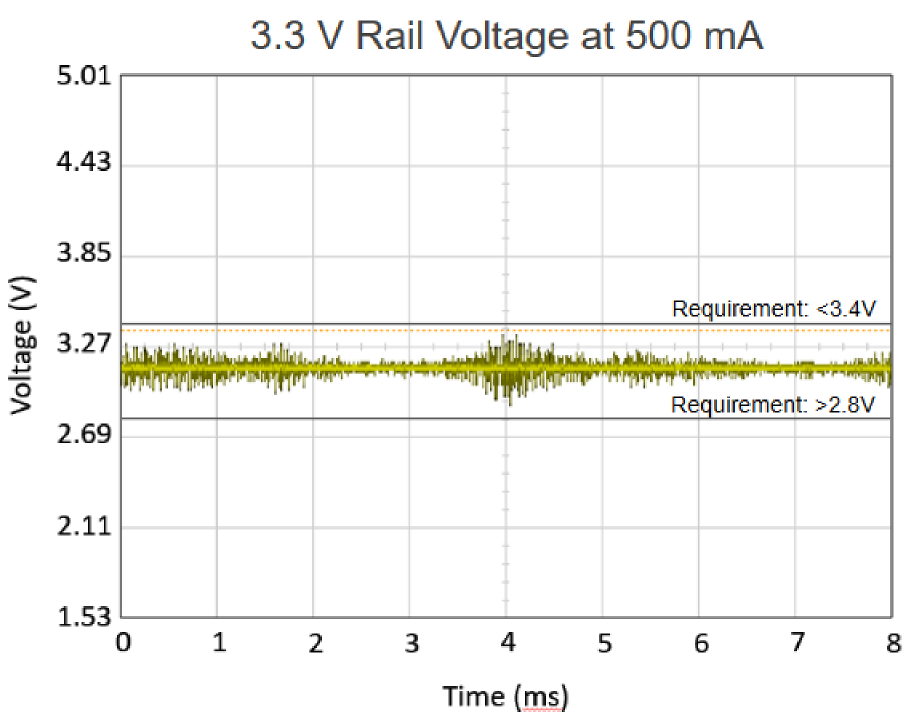


Figure 33: Oscilloscope reading of the 3.3 V power rail supplying 500mA.

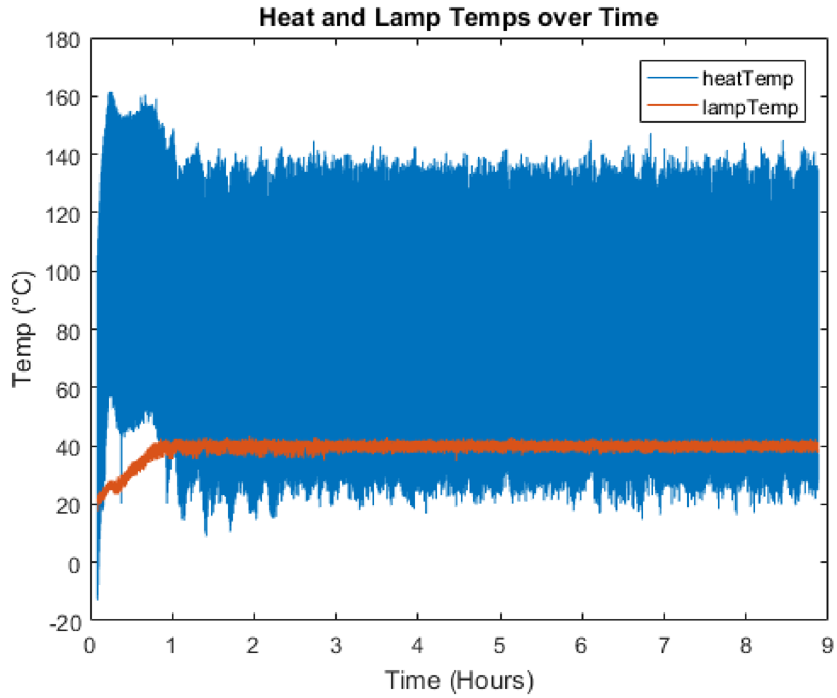


Figure 34: Raw, noisy sensor data from warm-up experiment of our lava lamp.

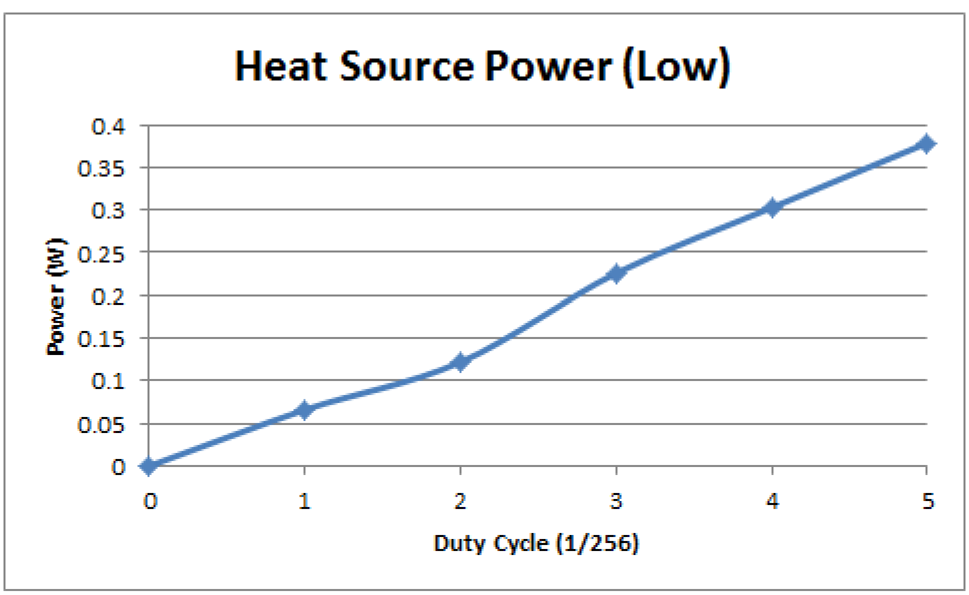


Figure 35: A sample of the heat adjustment for the low range PWM settings.

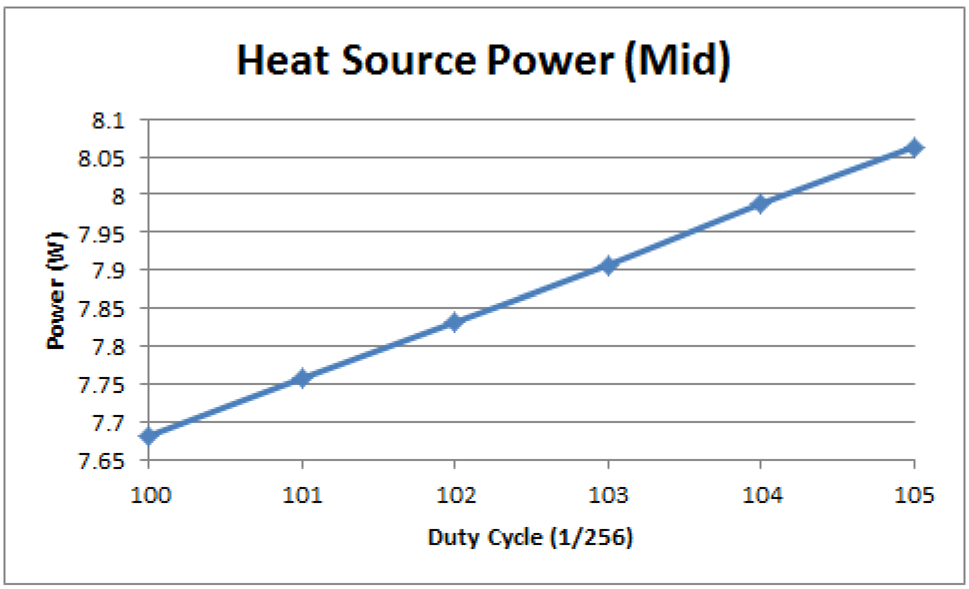


Figure 36: A sample of the heat adjustment for the middle range PWM settings.

Table 5: TMP36 temperature sensor accuracy test

Reading	IR($^{\circ}C$)	Sensor($^{\circ}C$)
1	25.4	25.6
2	25.0	24.1
3	24.3	23.0

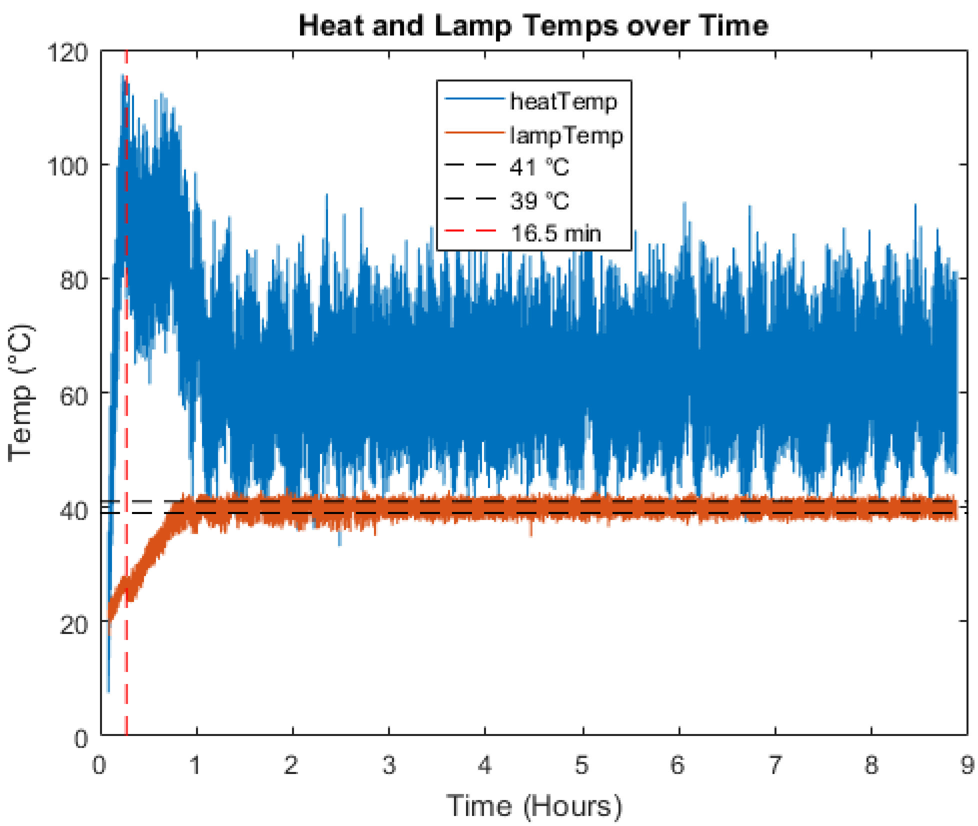


Figure 37: Plot of the heat source temperature and lava lamp temperature vs. time for a full warm-up experiment

Figure 38: Frame 183 from the time-lapse video of the full warm-up experiment. This shows the first movement of the lava globules at an elapsed time of roughly 11.5 minutes.

Appendix G Assembled PCB

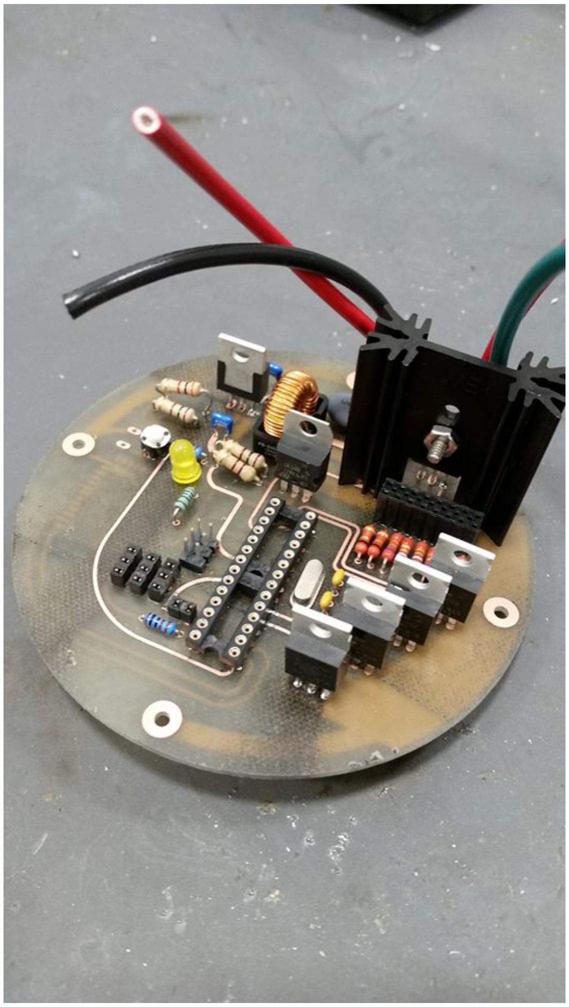


Figure 39: Manufactured and assembled PCB, view of top side

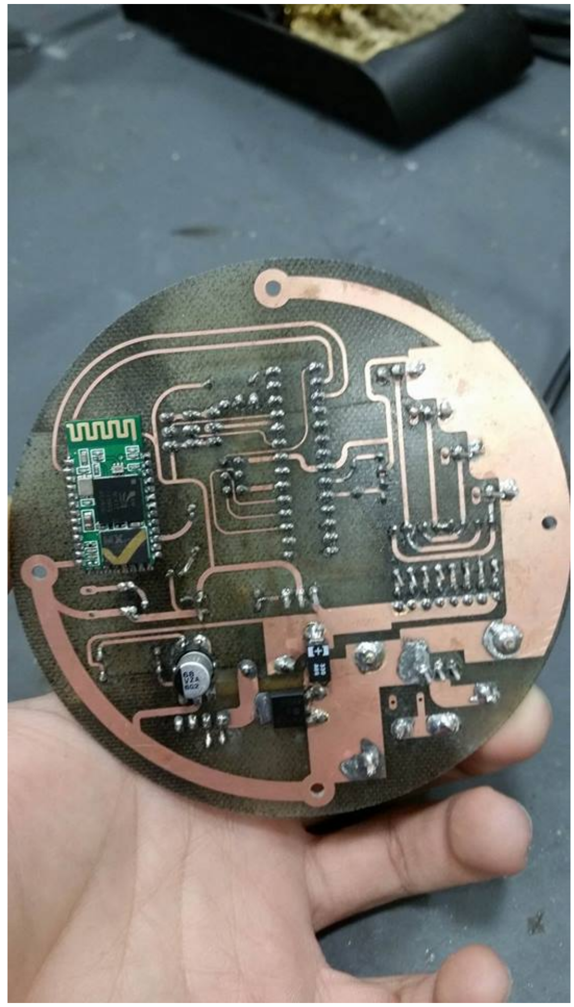


Figure 40: Manufactured and assembled PCB, view of bottom side

Appendix H Acknowledgements

Throughout this semester we have been blessed to have such helpful people on our journey. In no particular order here are some of them.

Our lovely TA: Jamie Norton

ECE Machine Shop: Skee G. Aldrich & Scott A. McDonald

Industrial Design Team: Sarah Spalding, Jarek Diaz, Jill Moore, and Lucas Mai

Additional TA's: Jackson Lenz, Katherine OḰane, Luke Wendt, and Zipeng Wang (Bird)

This project would not have been such a success without the help and guidance of these men and women.