Electronics I – Design Project Report

Pre-Shower Water Heater

Department of Electrical and Computer Engineering

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Abstract

In this report a revolutionary, state-of-the-art and practical solution to heating water is presented. The goal of this solution was to provide a useful and creative function utilizing only analog components and a dynamic 555 timer while not exceeding a total cost of $10.

The proposed method utilizes the 555 timer as well as the principles of negative feedback loops in order to heat water to any temperature the user desires while providing them with a convenient user interface that indicates when the water has reached the desired temperature. It is shown that by utilizing the functions of versatile circuit elements such as operational amplifiers, Zener diodes, NMOS transistors, solid state relays, and LEDs, a cost-effective and environmentally friendly circuit that performs a practical function can be manufactured and implemented with the potential to save trillions of litres of clean water each year.

Through simulations as well as real-world prototype testing presented in this report, it is demonstrated that this unique and adaptable circuit solution has very real and important applications that have the potential to immediately solve everyday problems faced by people in modern day society.

Collaboration and Participation

The conceptualization and development of the project was the result of dedication and creativity demonstrated by both team members. Both individuals were present during each brainstorming session, worked together to solve problems that arose, and strived to attain results while fine tuning the design during each testing session. Each team member took responsibility for the following duties:

Eric Parker

I. Defining, developing, and researching the overall goal of the project and its potential implications
II. Design and synthesis of the switching performance of the circuit
III. Design and synthesis of the LED heater performance indication of the circuit
IV. Design and synthesis of the AC powered relay controlled circuit
V. Component research, choice, and acquisition
VI. Deciding upon the design that best met the goal of the project

Sean Santarossa

I. Research of theoretical principles governing circuit behaviour
II. Design and synthesis of the 555 timer circuit in astable operation
III. Performing LT Spice simulations
IV. Development of overall project constraints
V. Implementation of design improvements during testing

Together, both team members were not restricted to the activities listed above; rather each member contributed to every challenge faced in order to ensure the overall goals and constraints of the project were met.

Table of Contents

Introduction

From the moment the project was first introduced, it was mutually understood by both team members that the goal was to design a circuit that could solve a significant problem encountered daily by many individuals all around the world. One particular field that the team felt could face increasing problems in the future is resource management. Although engineers in modern society are very good at solving such problems and have successfully done so in the past in a number of different fields, as the world's population continues to increase, engineers must push the limits of ingenuity in order to sustain suitable living conditions for the many generations to come. An increasing human population means an increasing demand for valuable resources necessary for the wellbeing of every person on earth. This means engineers must create new ways to reduce the use of such resources in order to develop the sustainable infrastructure necessary to accommodate everyone.

One way engineers can accomplish this daunting task is to develop environmentally friendly solutions to everyday problems to reduce the demand for resources; one of the most important resources being clean water. As engineers, it is important to understand the power of one. That is, a single individual decreasing the quantity of a resource they use may seem extremely insignificant when compared with the demands required by the entire world, however as more individuals partake in such practices, it has the effect of multiplying the impact each person has millions or even billions of times over leading to drastic reductions in the demand for a given resource. Put simply, small changes add up… significantly. With this in mind, the team began researching simple ways in which people could decrease their demand for valuable resources by just a little bit each day.

Almost immediately, the team exposed one way in which every household could significantly reduce the use of clean water simply while increasing home comfort at the same time. It is very common practice for people to allow the shower to run for about one minute to allow the water to become a comfortable temperature before entering. According to the Environmental Protection Agency (EPA), every minute that a standard shower head is run equates to 2.5 gallons [1] (approximately 9.5 litres) of water. This means that 9.5 litres of water are wasted for every minute that a person spends outside of the shower waiting for the water to heat up to a comfortable temperature; this type of water waste is referred to as "behavioural waste" by the EPA [2]. If every person in the United States and Canada took 6 showers a week on average (the national average number of weekly showers taken per person for both America and Canada is well above 6 [3], [4]) and each individual waited just one minute before stepping in to the shower to allow the water to become a comfortable temperature, this equates to approximately 1.05 trillion litres of water wasted annually by the United States and Canada alone [5]! As mentioned previously, this is a fine example of how simple changes add up. A similar behavioural waste is created by cooking and handwashing, thus further contributing to the total volume of clean water wasted each year due to behavioural waste. Needless to say, something needs to be done to eliminate this horribly irresponsible waste of water.

The objective of our project was to address this issue by developing a way to provide people with water at a comfortable temperature immediately out of the shower or sink tap without any delay allowing individuals to enter the shower or wash their hands comfortably the instant they turn the water on. The general concept behind the design is the user can set the desired temperature of the water, and this will immediately energize a water heater (this operation is also indicated by a LED being turned on). Once the water gets to the desired temperature, the circuit will automatically turn the water heater off and indicate that the water has been heated to the correct temperature by flashing the LED on and off repeatedly.

After further research was done, it appeared that there were very few solutions designed to perform such a task. Hence, the idea that could change the world began to formulate. While researching, the team discovered that while there were multiple circuits designed to indicate water levels, no practical circuit configurations were designed for the purpose of heating water; all of the circuits that had anything to do with heating water were either intended for industrial use, or were far too inefficient or slow for any kind of practical use. The majority of the circuits found tried to utilize solar power in order to heat water which is very insightful since solar power is both abundant and renewable, however solar power is nowhere near strong enough to supply a heating element capable of heating water in a timely manner. Some circuits shown utilized triacs (a common circuit element in today's industry) as shown in Figure 1 and 3 but failed to show practical applications for the everyday household use. Clearly, an entirely new design was required for efficient and reliable household use.

The team's design is incredibly simple requiring only one temperature sensing element, an op-amp, an LED, a 555 timer, a relay, a transistor, and (of course) a water heater. Perhaps the most important component of the circuit (as far as accuracy is concerned) is the temperature sensing element. For this, a thermistor could have been used but its resistance changes non-linearly with temperature which would make it very difficult to heat water accurately to a desired temperature. Instead, an LM335 circuit element, which is a specialized Zener diode designed to measure temperature, was used because it accurately measures temperature linearly which is much more desirable. The output voltage of the LM335 (which the voltage across the Zener diode wired in reverse-bias) is exactly equal to $10\, mV/K$. That is, the output voltage increases by $10\, mV$ for every 1 degree Kelvin increase in temperature. For example, room temperature ($25°\text{C} = 298\, K$) would yield an output voltage of $298\, K\ \cdot 10\ \ mV/K = 2.98\, V$ accurate to within $1°\text{C}$. This linear performance enables the design to heat water to literally any desired temperature with great accuracy.

The switching performance of the circuit is achieved by wiring the output voltage of the LM335 temperature sensor to the inverting terminal of an op-amp, and applying an input voltage corresponding to the desired temperature to the non-inverting terminal of the op-amp. When the input voltage at the non-inverting terminal is greater than the output voltage of the temperature sensor, the op-amp is saturated positively thus yielding a large positive output voltage (this will be referred to as a "high" output). Conversely, if the output voltage of the temperature sensor is greater than or equal to the input voltage, the op-amp is saturated negatively thus yielding a large negative output voltage (this will be referred to as a “low” output). Because the temperature sensor is configured to measure the temperature of the water, the only way the output voltage goes low is when the temperature of the water is equal to the desired temperature, which can be adjusted by changing the input voltage applied at the non-inverting terminal of the op-amp.

In order to translate this switching into efficient water heating, the output voltage of the op-amp is wired to the gate of a NMOS transistor. When the op-amp output is high, the transistor is on; when the op-amp output is low, the transistor is off. Finally, wiring a relay to the drain of this NMOS transistor controls switching of an adjacent circuit that uses AC power from any ordinary household outlet to energize a very powerful, efficient water heater that can quickly heat large quantities of water. Lastly, the 555 timer is used to indicate completion of this process; once the water is at the desired temperature, the indicator LED (which was constantly on while the water heater was energized) begins flashing.

Design Objectives

1. Effectively and efficiently heat water from a conventional sink or shower head in modern day houses
2. Allow the user to manually set the temperature of the water to any desired value
3. Indicate when the water is heating and when the water has reached the desired temperature using an LED
4. Utilize a negative feedback loop in order to hold the water at the desired temperature until the user turns it off and no longer wants the water heated
5. Be able to easily install and access the circuit without the circuit causing harm to the user even if the circuit is exposed to water

State of the Art

From the research conducted by the team, the majority of the circuits that involved heating water were either intended for industrial use, or were too inefficient or slow for any kind of practical use. Many of the designs found used solar panels in order to heat geysers of water which serve as economical but impractical solutions to this problem due to the fact that the available technology for solar energy is still far behind that of other forms of energy and thus most circuits that implemented solar panels did not have the speed necessary to meet the demands of the everyday consumer.

Other circuits encountered by the team were dependant on digital components and microcontrollers or involved expensive components such as transformers. The following figures outline circuits the team found that had features and concepts that could potentially prove useful to the team's final design.

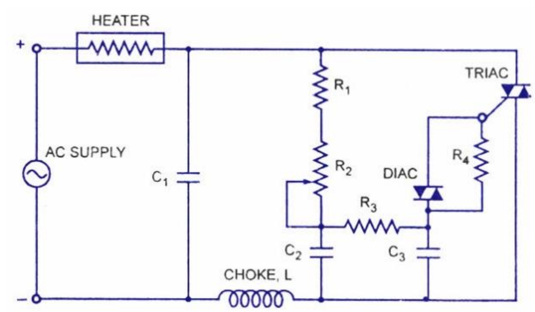

Figure 1 – Heating Circuit that Used Dirac

The circuit in Figure 1 is a circuit that powers a heater using an AC supply [6]. This circuit uses a "triac" controlled by an RC phase shift network. The triac conduction angle is adjusted by adjusting the potentiometer R_2; the longer the triac conducts, the hotter the heater will get. Although the team liked the idea of controlling an AC power source with a circuit element, the circuit lacked a feedback loop and used both a choke and a triac which are expensive circuit elements. This circuit also lacked an indicator to notify the user when the water was heated.

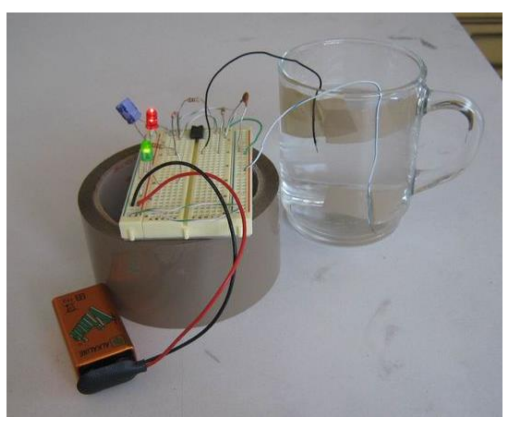

Figure 2 – Circuit for Water Level Indicator

The circuit in Figure 2 was another circuit discovered by the team that had features and components that could prove useful [7]. The circuit is a water level indicator and although it lacks the ability to heat water, it uses a 555 timer as well as a negative feedback loop to indicate the level of the water in the cup. The design was simple and utilized the 555 timer as well as LED lights to interact with the user.

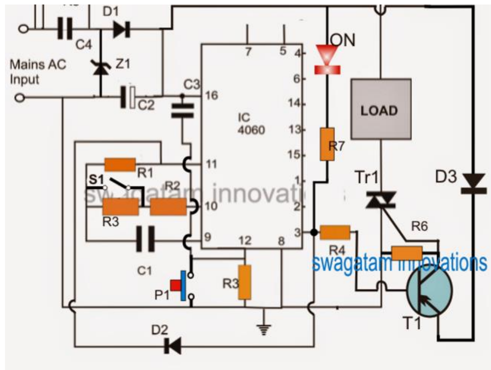

Figure 3 – Heating Circuit with Microcontroller

The last circuit that the team saw potential in was the circuit shown in Figure 3. This circuit design also heated water using AC power and utilized a triac similar to the circuit discussed in Figure 1 however this circuit used the IC 4060 as a time delay generator configured in a one shot monostable timer for the circuit [8]. This means that the heater was turned on for a set period of time rather than until the water reached a specific temperature which did not seem as useful. This circuit is powered by a transformerless power supply which implies that every point in the circuit may be floating at mains AC level and could produce a lethal electric shock which was also a concerning issue present in this circuit.

Values and Constraints

Table 1 – Circuit Elements Used Cost

Name of Circuit Element	Amount	Cost of Circuit Element ($)
Relay	1	3.72
Water Heater	1	2.49
Op-Amp (LM741)	1	0.00
Temperature Sensor (LM335)	1	0.89
Diodes (1N4003)	3	0.00
LED	1	0.00
Transistor (ZVN2110A)	1	0.00
Capacitor	1	0.00
Resistors	5	0.00
Potentiometer	1	0.00
Switch	1	1.49
Electrical Outlet	1	0.89
Total	--	9.48

Constraints:

1. Time constraint
   a. 12 weeks

2. Money constraint
   a. $10 budget

3. Analog components only

4. Limited supplies

5. Range
   a. Must be able to heat liquid water to any desired temperature

6. Accuracy
   a. For safety purposes, must be able to heat water to a desired temperature within a few degrees Celsius

7. Speed
   a. Must be able to heat large volumes of water very quickly

Deliverables

1. Effectively and efficiently heat water from a conventional sink or shower head in modern day houses.

   Through the use of a powerful water heater and an AC power source controlled by a relay which in turn in controlled by the circuit design

2. Allow the user to manually set the temperature of the water to any desired value

   The user sets the desired temperature manually by changing the voltage applied to the non-inverting terminal of the op-amp which can be done through an external component connected to the circuit

3. Indicate when the water is heating and when the water has reached the desired temperature

   An LED light is attached to the circuit in order to indicate when the water is heating (the LED is constantly on) and when it is done (the LED flashes).

4. Utilize a negative feedback loop in order to hold the water at the desired temperature until the user turns it off and no longer wants the water heated

   Until the potentiometer is turned high (meaning the user does not want the water heated), the voltage at the non-inverting terminal of the comparator will be at the voltage that corresponds to the temperature the user wants the water heated to and hence the circuit will use the negative feedback loop of the temperature sensor to always maintain that voltage.

5. Be able to easily install and access the circuit without the circuit causing harm to the user even if the circuit is exposed to water

   The simple design of the circuit and the safety switch connected to the AC circuit of design ensures easy installment and safe operation whenever the user is handling the circuit

Design Methodology

I. TEMPERATURE SENSING

In order for the circuit to heat water to a very specific temperature, it must first be able to *measure* temperature within the desired tolerance. Thus, the accuracy of the circuit is completely limited by the temperature sensing component used. To ensure accuracy, an LM335 precision temperature sensor was chosen because of its very small measurement tolerance and its linear operation. An LM335 is a specialized Zener diode whose output voltage changes linearly according to the measured temperature in degrees Kelvin [9]. The output voltage of the LM335 is exactly equal to $10\,mV/K$. That is, the output voltage increases by $10\ mV$ for every 1 degree Kelvin increase in temperature. For example, room temperature ($25℃ = 298\ K$) would yield an output voltage of $298\ K\ \cdot 10\ mV/K = 2.98\ V$ accurate to within 1℃. This linear performance combined with a large range of possible values allows for the design of a circuit that can heat water very accurately to literally any desired temperature.

II. SWITCHING PERFORMANCE

The switching performance of the circuit is achieved by wiring the output voltage of the LM335 temperature sensor to the inverting terminal of an LM741 op-amp, and applying an input voltage corresponding to the desired temperature to the non-inverting terminal of the op-amp. When the input voltage at the non-inverting terminal is greater than the output voltage of the temperature sensor, this means the voltage at the non-inverting terminal is larger than the voltage at the inverting terminal. Contrarily, when the output voltage of the temperature sensor is greater than or equal to the input voltage at the non-inverting terminal, this means the voltage at the non-inverting terminal is smaller than the voltage at the inverting terminal. Since no resistors are used in the configuration, the closed-loop gain of the op-amp is very large. Thus, when the voltage at the non-inverting terminal is larger than the voltage at the inverting terminal, the output of the op-amp is saturated at the maximum positive voltage. Conversely, when the voltage at the inverting terminal is larger than the voltage at the non-inverting terminal, the output of the op-amp is saturated at the maximum negative voltage.

The output of the LM741 op-amp is then wired directly to gate of an NMOS transistor (ZVN2110A) that has a relay connected to its drain node. If the output of the op-amp is saturated at the maximum positive voltage, the transistor's gate voltage is large enough to turn the transistor on and enable operation in the saturation region. In doing so, current energizes the relay which completes a switch wired in an adjacent circuit that uses AC power from an ordinary household electrical outlet to power a powerful water heater. Conversely, if the output of the op-amp is saturated at the maximum negative voltage, the transistor's gate voltage is negative. Since the source node of the transistor is wired to the circuit ground, the condition $V_{GS} > V_{tn}$ is not satisfied and the transistor is turned off meaning that no current can flow through the relay therefore not completing the adjacent water heating AC circuit which results in not turning the water heater on.

Since the input voltage applied to the non-inverting terminal of the op-amp is being directly compared with the output voltage of the LM335 temperature sensor, and the output voltage of the LM335 component is determined by the equation $V_o = (10\ mV/K) \cdot T$ where T is the temperature in degrees Kelvin, this means the user can attain any desired temperature he/she desires by applying an input voltage determined using the equation for V_o. For example, if the user wanted to heat water to exactly $320\ K$, they should apply $V = (10\ mV/K) \cdot 320 = 3.2\ V$ to the non-inverting terminal of the op-amp. This is because the heater will only turn off when the output voltage of the op-amp is low, and this only happens when the output voltage of the temperature sensor V_o is greater than or equal to the voltage at the non-inverting terminal of the op-amp. Therefore, by using the equation that governs V_o, the user can specify the exact temperature that they want the water heated to, and the circuit's design will ensure that the water heater will automatically turn off when the water reaches the desired temperature. Note that a potentiometer is used in the circuit configuration to allow the user to change the input voltage to the non-inverting terminal of the op-amp by simply rotating the dial on the potentiometer. This has the effect of decreasing the resistance which increases the input voltage to the non-inverting terminal of the op-amp, or vice versa.

The switching performance of the circuit is summarized in the following flow chart. Assume that the water is initially at room temperature and the user wishes to heat the water to a temperature higher than room temperature:

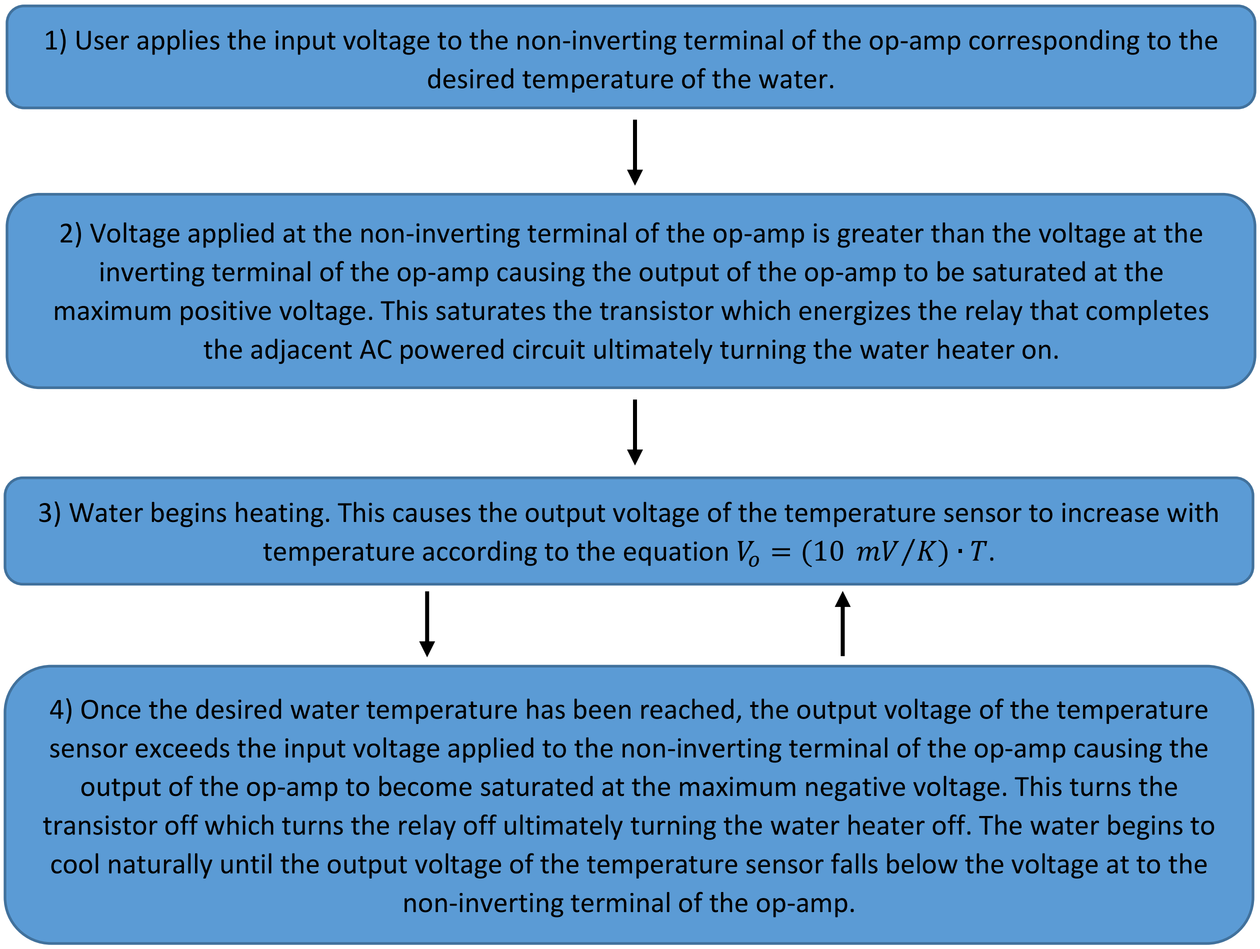

Figure 4 – Switching Performance of the circuit

As indicated by the arrows between step 3) and step 4), the circuit will continue to hold the water at the desired temperature until the user stops applying an input voltage to the non-inverting terminal of the op-amp.

III. LED HEATER PERFORMANCE INDICATION

An LED was added to the design in order to improve the user interface of the circuit by indicating which region of operation the circuit is operating in. The design of this portion of the circuit was developed to achieve the following behaviour:

1) When the user does not want to heat water, the LED is OFF.
2) While the water is heating, the LED is ON.
3) When the water reaches the desired temperature, the LED flashes on and off repeatedly.

The purpose of this behaviour was to ensure the user knows exactly which function the circuit is performing at all times and to allow the user to know when the water is at the desired temperature. In order to achieve the desired behaviour specified above, the LED was wired directly to the output of op-amp. That way, whenever the output of the op-amp is high (meaning the water heater is on) the LED is on and whenever the output of the op-amp is low (meaning the water heater is off) the LED is off. Next, to create the flashing light operation, a 555 timer circuit was configured in astable operation in order to achieve an output that goes high for some amount of time, and then low for an equal amount of time; this type of operation is perfect for creating flashing lights [10]. The output of this astable 555 circuit configuration was also wired directly to the indicator LED. Thus, when the output of the op-amp is high *and* the output of the astable 555 timer circuit continues fluctuating, the output waveform of the 555 circuit is completely masked by the constant DC voltage applied by the output of the op-amp. Conversely, when the output of the op-amp is low, only the output waveform of the 555 timer circuit powers the LED causing the LED to flash on and off repeatedly. In doing this, it allowed the circuit to create operation 2) and 3) of the desired behaviours indicated previously. Finally, to achieve the final desired operation, the node powering the 555 timer circuit in astable operation was wired directly after the potentiometer to the input voltage set by the user. Thus, when the user did not apply an input, both the 555 timer circuit was not powered and the output voltage of the op-amp was low, ultimately meaning the LED is completely off.

The LED heater performance indication of the circuit is summarized in the following flow chart. Assume that the water is initially at room temperature and the user wishes to heat the water to a temperature higher than room temperature:

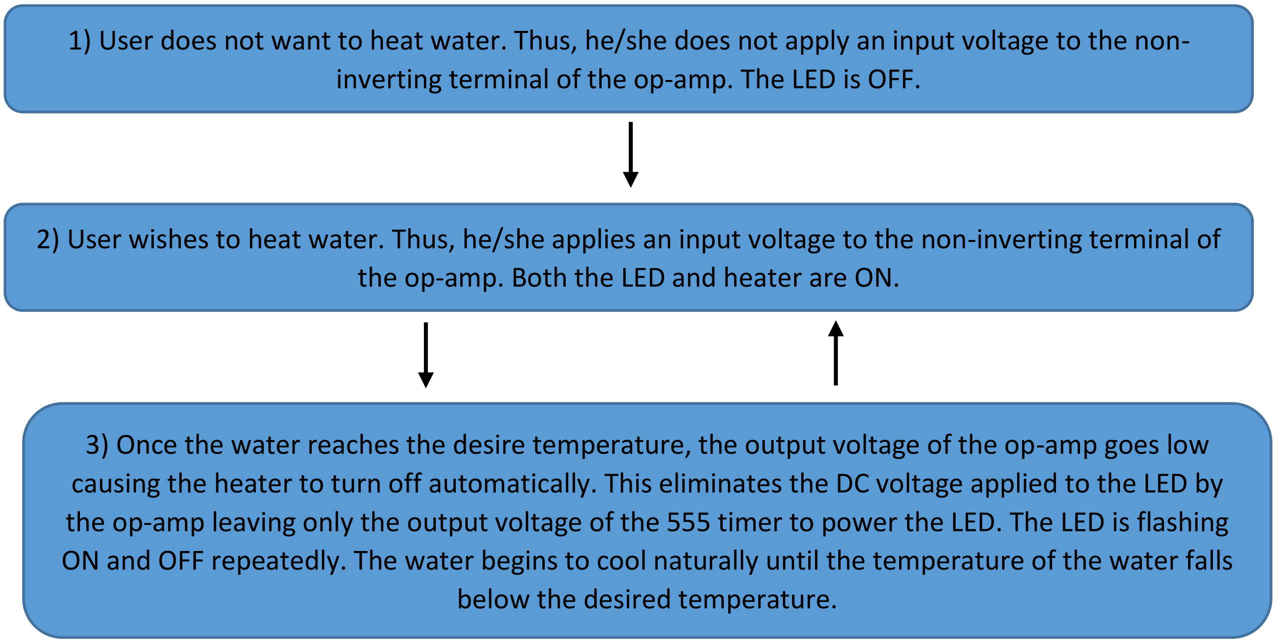

Figure 5 – LED Indication Performance of the circuit

It is important to note that diodes are used to prevent current from travelling back into the outputs of both the op-amp and the 555 timer. This guarantees that all current must flow through the LED in order to get to ground, thus ensuring that the desired behaviour of the LED is established.

Physical Implementation

The physical implementation of the design was easily fabricated by following the schematic outlined in Figure 7. In order to ensure success, each major portion of the circuit was fabricated and tested individually before combining the circuits and completing the model. First, a standard 555 timer circuit in astable operation was created and tested using an LED. Once this was completed, the op-amp comparator circuit was fabricated and tested by applying relatively low input voltages and heating the temperature sensor until the output of the op-amp went low. Finally, the performance of the transistor-relay circuit was tested alongside the AC heater circuit by applying small AC signals using the Analog Discovery kit for safety purposes. Once the performance of each individual portion of the circuit was verified, combining each to form the final design was trivial and success was achieved almost immediately therefore verifying the validity of the overall design. However, to get the circuit heating water to precise temperatures, much testing and calibration of the temperature sensing portion of the circuit was required.

In order to ensure accuracy of the temperature sensing component of the circuit, the LM335 temperature sensor was calibrated such that the output voltage at room temperature (25°C) was above $2.98\ V$. This would ensure proper sensor performance. To verify the circuit's operation, a large metal pot was filled with water at room temperature and the heating element was placed in the water. The temperature sensor was then attached to the metal pot. Because metals are excellent heat conductors, the temperature of the pot is always approximately equal to the temperature of the water. The goal of one documented trial was to heat the water to $120°\mathrm{F}$. Since $120°\mathrm{F} \approx 322\ K$ and the output voltage of the temperature sensor is determined by the equation $V_o = (10\ mV/K) \cdot T$, this means the user should set the input voltage applied at the non-inverting terminal of the op-amp to $V = (10\ mV/K) \cdot 322\ K = 3.22\ V$. Thus, the Analog Discovery kit was used to apply this voltage.

As expected, applying this voltage caused the water heater and the LED to turn on and the water began heating. As the temperature of the water increased, so did the output voltage of the temperature sensor. Once the output voltage of the temperature sensor reached $3.22\ V$, the water heater turned off and the LED began to flash as expected. To ensure the water was at the correct temperature, a thermometer was used to measure the temperature of the water and it was almost exactly at $120°\mathrm{F}$. These results can be seen below in Figure 14, Figure 15, and Figure 16 in the *Proof of Design* section of this report.

After fabricating the physical implementation of the circuit, a very important observation was made. Because the design of the AC portion of the circuit was completed using a standard household electrical outlet, the circuit has many applications besides simply heating water. Literally any temperature dependent process can be carried out using this design. Put more generally, this circuit's overall design is to energize a relay which completes an AC circuit until the temperature sensor measures a particular temperature. Therefore, this circuit can be used for almost any application that requires an electrical load to shut off at a certain temperature.

For example, this exact same circuit could be used to create a device that shuts off a toaster oven when food reaches an exact temperature; the only required changes to the design being that the temperature of food would need to be measured instead of the temperature of water and the AC circuit powers a toaster oven instead of a water heater. Such a circuit would prevent overcooking and save energy simply by turning off the toaster oven the moment the food is done cooking. It also ensures food safety as it is recommended that some meats be cooked until they are above a certain temperature.

The design can also be used for cooling processes, not just heating. Altering the design slightly by simply wiring the output of the temperature sensor to the non-inverting terminal of the op-amp and the input voltage to the inverting terminal (which is opposite to the design proposed in this report), the output of the op-amp becomes high when the output voltage of the temperature sensor is greater than a certain value, essentially creating a circuit that can be used for virtually all cooling processes, and this was attained simply by switching two wires! Such a circuit could be used to create a computer heat sink. By measuring the temperature of a computer processor and powering a fan instead of a water heater, the fan would turn on the moment the temperature of the processor becomes greater than a certain value. The fan would then work to cool the processor and would automatically turn off when the temperature of the processor falls below the desired value.

Experimental Results

Many results were obtained from the countless tests and simulations performed over the development process of the proposed design, however there are a number of results that the team feels truly characterize and highlight the progressive development of circuit. These results and simulations are shown in the following section.

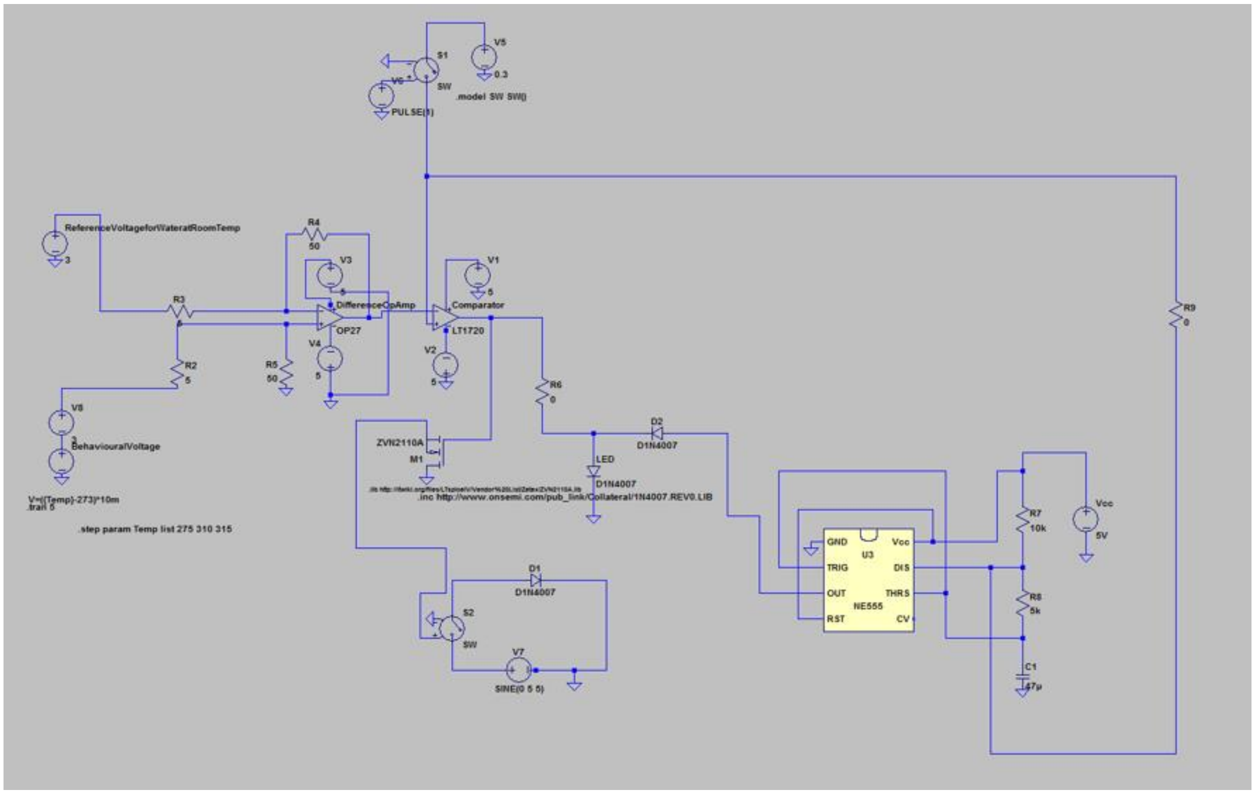

Figure 6 – Simulation of Prototype Circuit Design

The circuit shown in Figure 6 was the prototype design of the circuit presented in the project's proposal. However some compromises were made in the simulation due to the inability of modelling certain circuit elements in the software. These compromises will also be discussed throughout this section of the report.

The initial design made use of the difference op-amp as shown in the above circuit diagram. The voltage at the inverting terminal of the op-amp was originally a temperature sensor which would be exposed to the air of the room that the circuit was operated in. In the circuit schematic, the team used a constant voltage source of about 2.98V which corresponds to the approximate voltage that the temperature sensor would be outputting if it was in a room with an air temperature equal to 25℃. At the non-inverting terminal of this op-amp would be another temperature sensor attached to the container holding the water that was intended to be heated. The purpose of this difference op-amp was to amplify the difference between the temperature of the room and the temperature of the water. Initially the voltage of the two inputs would be equal since the temperature sensors would ideally always have the same reading since the temperature of the water would be equal to the temperature of the room it was in. This means the op-amps output would be ideally zero since the output voltage of a difference amplifier is:

$$V_{out} = \frac{R_4}{R_3}(V_+ - V_-)$$

The output of the op-amp was connected to the inverting terminal of the comparator which meant the voltage at the inverting terminal of the comparator would also ideally be zero initially. The voltage at the non-inverting terminal of the comparator would also be zero when the user did not want the water heated.

This setup was done so that whenever the user wanted to heat the water, they would turn the potentiometer and provide a voltage at the non-inverting terminal of the comparator. This would initially produce a high output at the comparator which would turn on the NMOS transistor (labelled ZVN2110A in the schematic) which would turn on the relay (represented as a voltage controlled switch labelled SW2 in the schematic) ultimately turning on the heater (represented by the diode labelled D1 in the schematic). As the heater increased the temperature of the water, the output voltage of the temperature sensor would increase and hence the voltage at the non-inverting terminal of the op-amp would also increase. As this voltage kept increasing, the output of the op-amp would also increase meaning the voltage at the inverting terminal of the comparator would increase. Once the voltage at the inverting terminal of the comparator exceeded the voltage at the non-inverting terminal of the comparator (which is held constant at the voltage set by the user), the output of the comparator would go low which would in turn shut off the heater. The main problem with this configuration was that the temperature of the water could never be set to a specific temperature. Due to the presence of the difference op-amp, the temperature of the water will always be relative to the temperature of the room. Thus, by turning the potentiometer different amounts, the user could only control how much hotter the water would be relative to the temperature of the room but not necessarily to an exact temperature value.

After reviewing the results and conducting numerous public surveys as well as comparing it to modern day electronic devices, the team decided to remove the difference op-amp in order to enable the user to set the temperature of the water to exact numeric values all while decreasing the overall cost of the circuit making the design much more cost-effective for the public.

Figure 7 shows the final design of the circuit simulated on the LT Spice software.

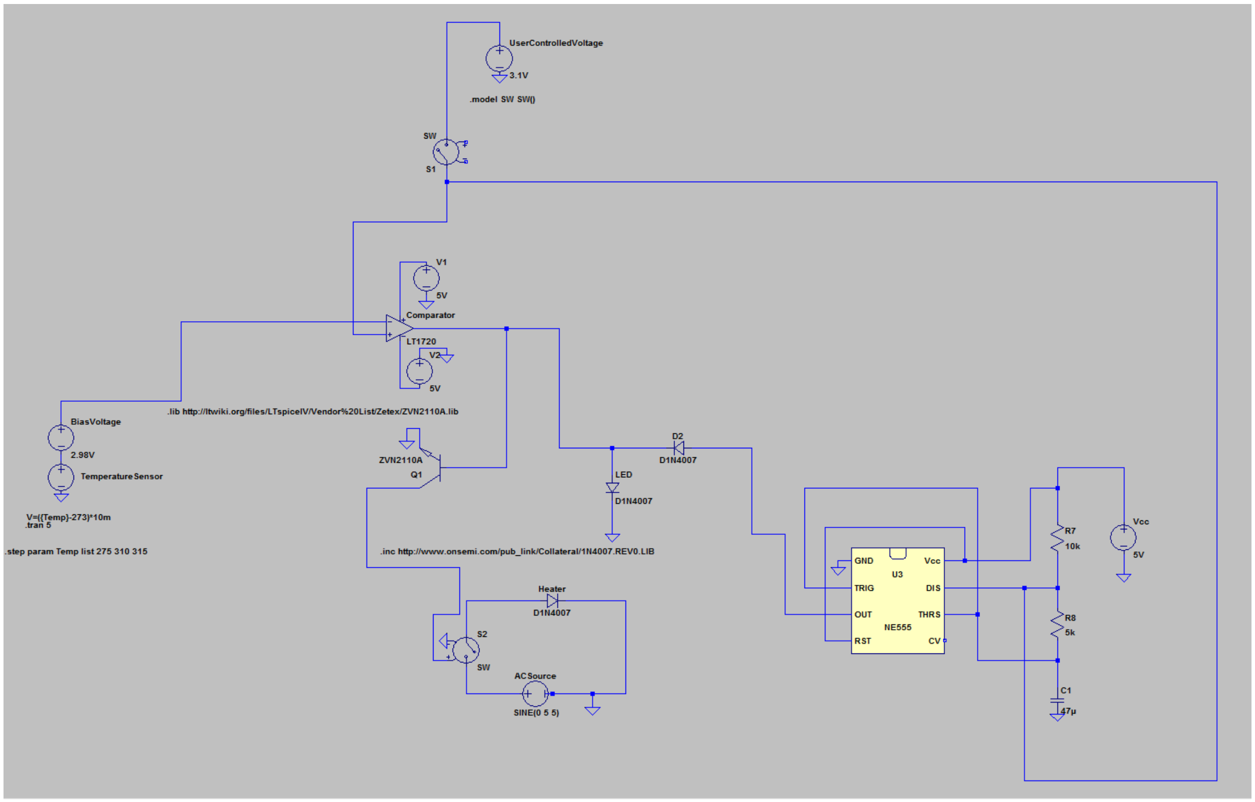

Figure 7 – LT Spice Simulation of Final Circuit Design

The design excluded the difference op-amp as well as the additional temperature sensor used for measuring the temperature of the air in the room. As mentioned previously, some compromises had to be made in order to account for the limitations of the LT Spice software. As can be seen in Figure 7, the temperature used to measure the temperature of the water was simulated by an arbitrary behavioural voltage source (labelled “TemperatureSensor” in the schematic) whose voltage depends on an algebraic expression equivalent to that of an LM335 temperature sensor. In the algebraic expression, the parameter “Temp” is used which represents the temperature of the water (in Kelvin) that the temperature sensor would be reading. By sweeping this parameter “Temp” the software can simulate what happens as the temperature measured by the temperature sensor increases as a result of the heater warming the water up.

Also in the schematic, instead of using a solid state relay, we used a voltage controlled switch called S2 to simulate it. The voltage controlled switch only turns on (which completes the AC circuit) when a voltage is present at its controlling terminals which are connected to the main control circuit. The final element that had to be compromised was the LM741 comparator. Instead, an LT10 comparator was used in the schematic however both have very similar properties and can be used in real world applications to produce similar if not exact results.

Prototype Specifications

The prototype control circuit shown below in Figure 8 is based off of the simulation in Figure 7. Figure 9 shows the accompanying AC powered circuit that is controlled by the relay in the control circuit. As discussed in more detail in the *Physical Implementation* section of this report, the prototype functions as expected within the accuracy restraints defined in the *Values and Constraints* section of this report. Although the circuit performed well, it required minor adjustments to ensure successful performance every time.

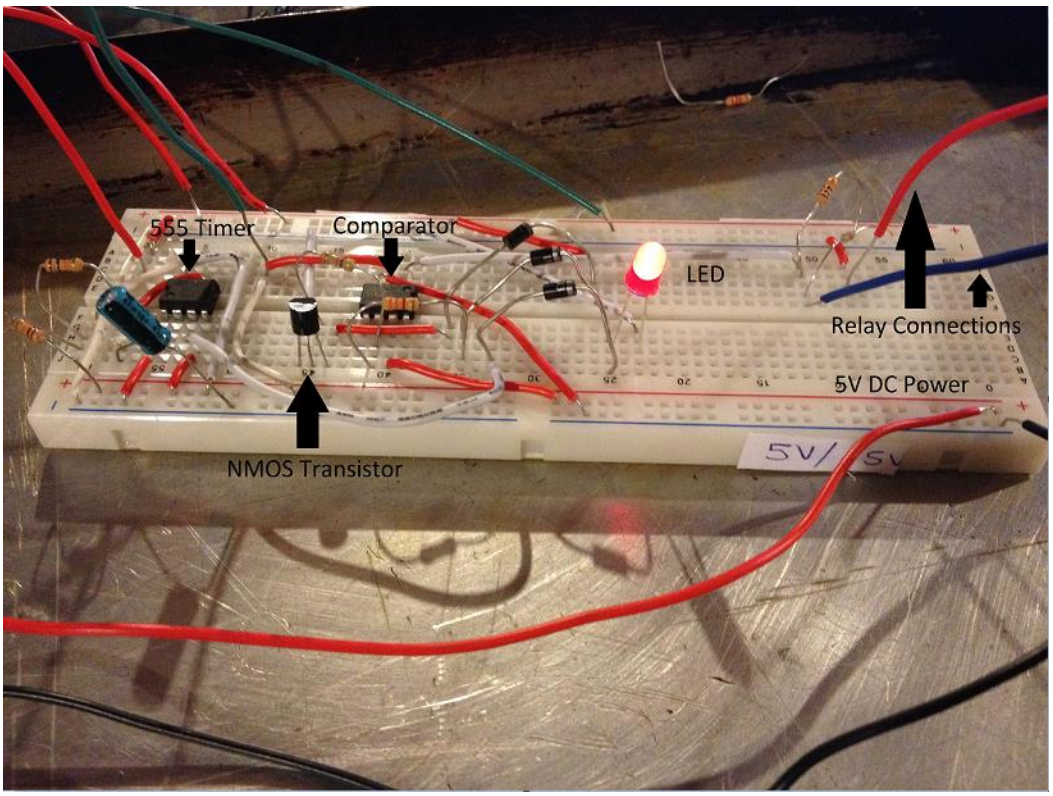

Figure 8 – Prototype Circuit

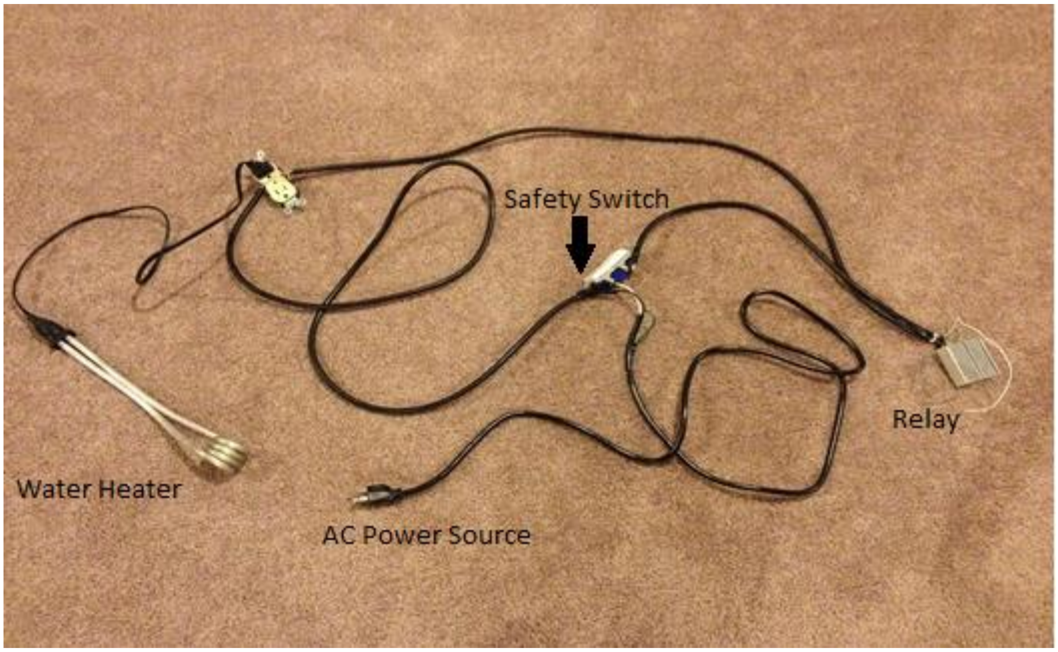

Figure 9 – AC Circuit

The first issue occurred when the water heating element would not turn on even when the relay was properly energized. After closer inspection of both circuits, this problem was due to a faulty connection to the switch of the AC circuit causing intermittent performance. The connection was reconstructed and the issue did not occur again.

A similar issue occurred when the relay would not turn off even when the output voltage of the op-amp was low. After individually testing each of the components involved, is was found that this issue was due to a faulty transistor and the issue was resolved by swapping the faulty transistor out for a new one.

Finally, an issue effecting the aesthetics of the user interface was resolved to improve the overall appeal of the final design. During testing, it was found that there was a great contrast in brightness of the indicator LED between when the LED was constantly on and when the LED was flashing on and off; the LED was much brighter when the LED was constantly on. After further measurements were taken, it was discovered that this problem was being caused by the difference in output voltage between the op-amp and the 555 timer. The op-amp's output voltage was measured to be approximately $2.8\ V$ whereas the output voltage of the 555 timer was measured to be only $1.8\ V$. This problem was resolved by adding a $3300\ \Omega$ resistor in series between the output of the op-amp and the diode connected to the LED. This resistor decreased the voltage seen by the LED due to the output of the op-amp enough to significantly dim the light when the output of the op-amp was high while still allowing this voltage to mask the voltage applied by the 555 timer in astable operation. By decreasing the contrast in brightness between the two different modes of operation, the flashing of the LED occurring when the water reaches the desired temperature seems much more pronounced.

Proof of Design

Final Design

The fully constructed physical implementation of the circuit design is shown in Figure 10.

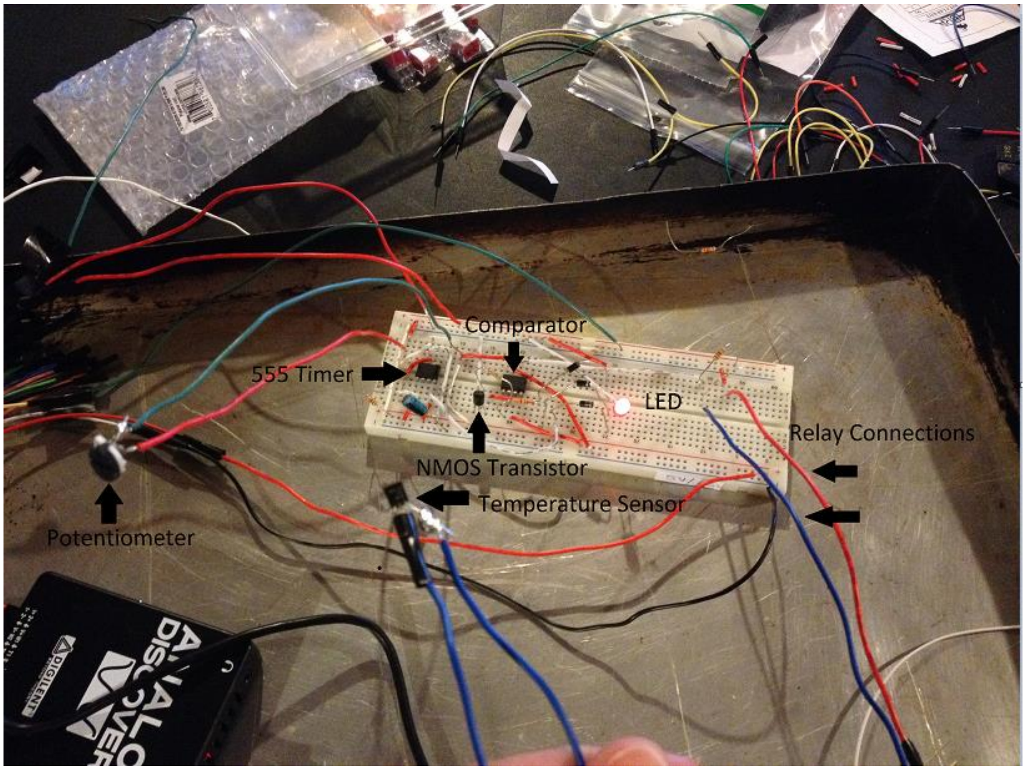

Figure 10 – Physical Model of Final Circuit Design

The circuit shown in the Figure 10 above was attached to an AC circuit which is shown in Figure 9 to produce the final circuit shown in Figure 11.

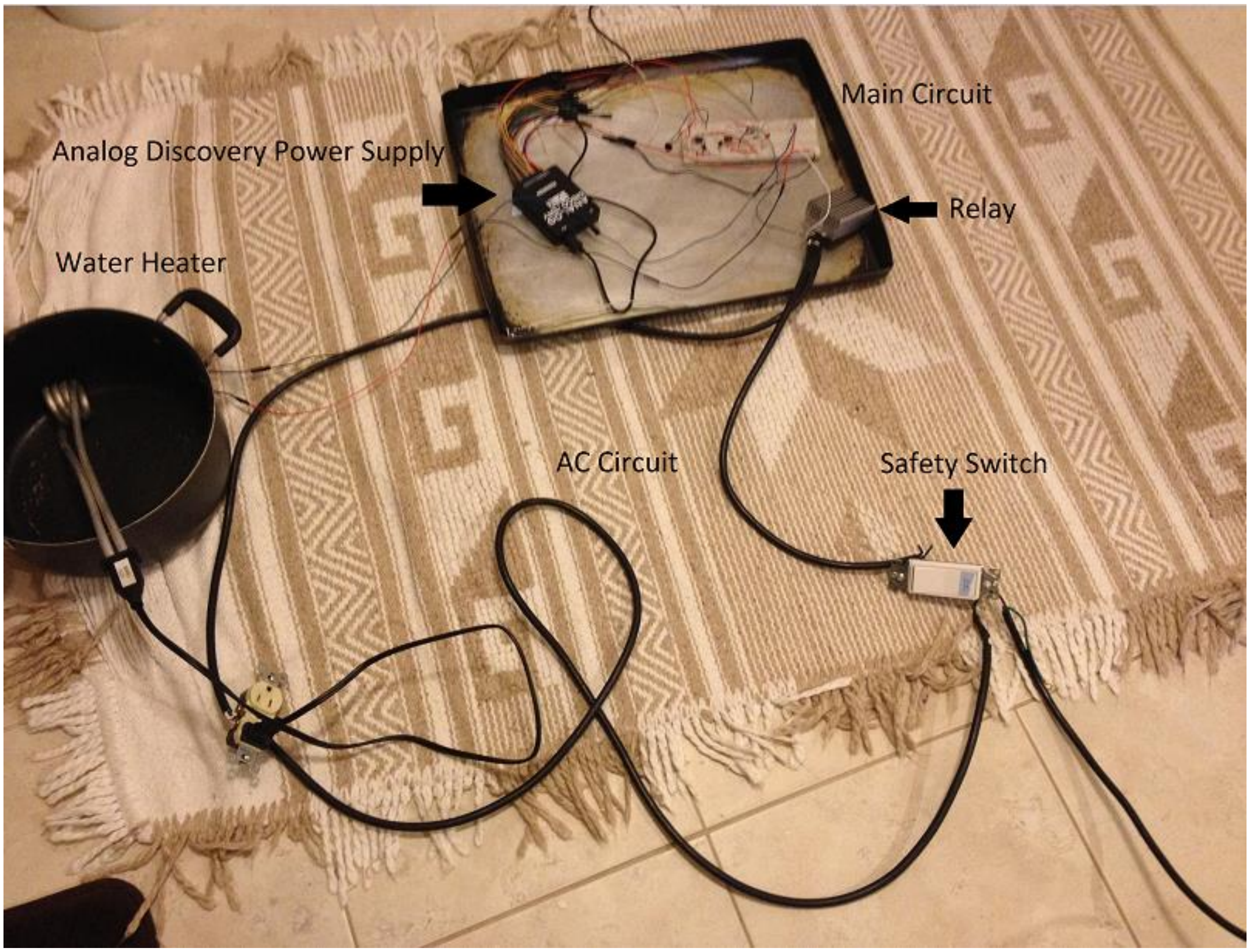

Figure 11 – AC Circuit Connected to Main Circuit

For demonstration purposes, the design uses the Analog Discovery kit for power and a cooking pot as the container for the water but these are just placeholders that could be interchanged with almost any industry standard devices. The design was tested in the environment that the team felt would most accurately represent the real world use of the design. The circuit was tested in a standard modern day household bathroom as if the circuit was to be used for heating the water of a bathroom sink or shower. The circuit performed exactly to the required specifications and expectations of the team.

Concept Demonstration

The following section will demonstrate and describe the process the circuit takes when the user wants to heat the water to the point in time when water is heated and finally to the point when the user no longer wants to heat the water.

Figure 12 shows the user turning on the potentiometer and consequently the LED turning on to indicate to the user that the water is heating. The temperature they wish to heat the water to is approximately 120ºF which corresponds to 3.22V being applied at the non-inverting terminal of the op-amp.

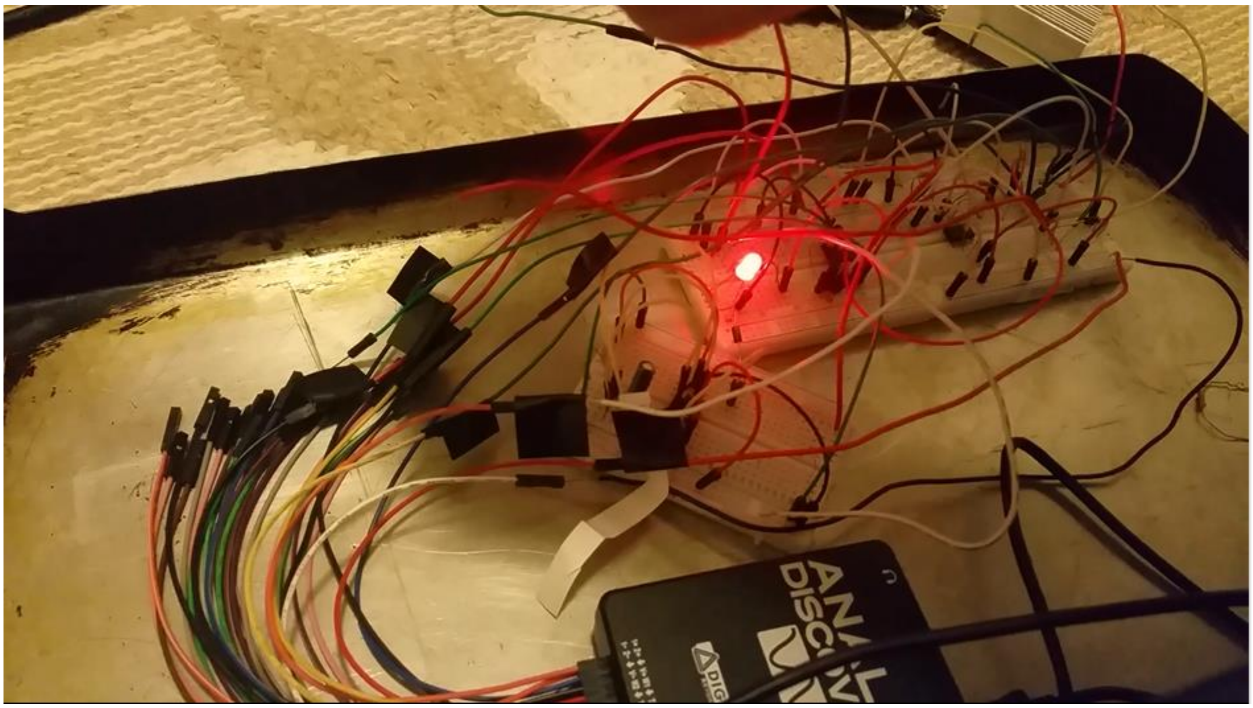

Figure 12 – LED Turning On when User turns Potentiometer

This light means the op-amp output is high and hence the heater turns on as shown in Figure 13 by the bubbles indicating that the heater is warming the water.

Figure 13 – Water Heater Heating the Water

Although the presence of bubbles is rather unclear in the pictures, another indication that the water heater is on can be seen by comparing Figure 14 with Figure 15.The initial temperature of the water is 100°F and it is heated to 120°F.

Figure 14 – Initial Temperature of the Water is 100°F

Figure 15 – Final Temperature of the Water is 120°F

Once the temperature has reached the required temperature of 120°F, the LED starts to flash on and off repeatedly at a slightly lower intensity indicated below in Figure 16.

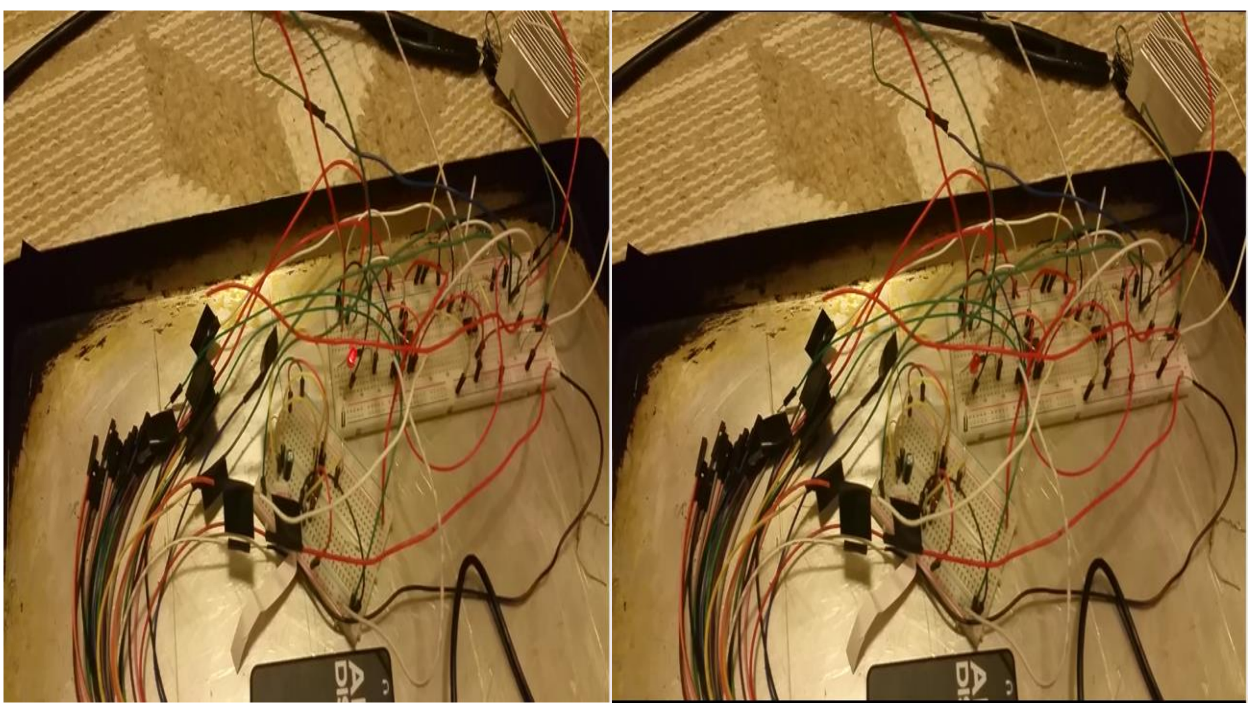

Figure 16 – The LED is Slightly less Bright and Flashing

At this point in the process, the potentiometer is still oriented to offer little resistance indicating that the user wants to hot water. Currently, the water is at the desired temperature of 120ºF (indicated by the LED flashing on and off repeatedly). At this point, the circuit will hold the temperature of the water at 120ºF until the potentiometer is manually turned off by the user; only then will the LED turn completely off. This setup is incredibly intuitive because the user will know exactly which state the circuit is operating in at all times, thus a high level of safety can always be maintained. When the LED is constantly on this means the water is heating and the user should take caution. When the LED is flashing on and off continuously, this indicates to the user that the water is ready but the circuit will still work to maintain the temperature of the water meaning the user should still take caution when dealing with the circuit because the heater may turn on at any moment (if the temperature of the water naturally falls below the desired temperature). When the LED is off this indicates to the user that the circuit is no longer heating the water and the circuit is safe to handle.

Conclusions

From the first team meeting, both team members had the goal of making this design as professional and efficient as possible to produce the best possible product for consumers. With this in mind, the team decided to use the Engineering Design Process Guidelines that are used by professional engineering teams in today's industry. This process is completed by following the steps and iterations outlined below:

1.) **Define the Problem**
2.) **Do Background Research**
3.) **Specify Requirements**
4.) **Brainstorm Solutions**
5.) **Choose the Best Solution**
6.) **Do Development Work**
7.) **Build a Prototype**
8.) **Test and Redesign**

The steps in this process can be repeated or referred back to as long as each step is completed and reviewed. The design was not completed or finalized until each of these steps were done to the best of the team's ability.

Define the Problem

This step was outlined by the proposal in that the final product had to be constructed from only analog components for less than $10 and the design had to include a 555 timer component. The problem was later refined by the team because the team wanted to create a product that had the potential to change the world. The team decided that the project had to be implementable in almost any household and could be used by almost everyone. The idea was to create a universal device that solves an everyday problem faced by billions of people.

Do Background Research

This step was done by both team members and can be seen in more detail in the *State of the Art* section of this report. By researching common everyday problems faced by consumers, the idea of heating water became prominent and evolved into the central focus of the team. By researching other projects and designs that involved heating water, the team took the best components from each in order create this hypothetical circuit that could perform functions that the team thought were important.

Specify Requirements

By reviewing and redefining the functions defined by the group in the *Background Research* step, the team came up with the most important functions that the circuit must perform which became the requirements of the design.

These requirements are defined in the *Design Objective* section of this report but are also repeated here for clarity:

- Effectively and efficiently heat water from a conventional sink or shower head in modern day houses
- Allow the user to manually set the temperature of the water to any desired value
- Indicate when the water is heating and when the water has reached the desired temperature using an LED
- Utilize a negative feedback loop in order to hold the water at the desired temperature until the user turns it off and no longer wants the water heated
- Be able to easily install and access the circuit without the circuit causing harm to the user even if the circuit is exposed to water

Brainstorm Solutions

The team then began brainstorming the possible solutions to each function. The team reviewed and re-evaluated these solutions and drew many different circuit diagrams that could potentially solve each function individually and then combined each individual circuit to form prototype circuits.

Choose the Best Solution

The best solution was found through the simulations done in LT Spice. By testing each prototype circuit in the simulation environment, the team was able to decide upon the best circuit design.

This was the step in which the team eliminated the difference op-amp. The simulations showed that the difference op-amp was not producing the required output and was essentially slowing the circuit down while adding cost to the circuit. This was also the step when the team decided to use the 555 timer as an indicator for when the water had reached the desired temperature. Before this point in the design process, the design only indicated that the water was warming but had no way of indicating that the water was done.

Do Development Work

The development work was done both by analyzing which circuit elements could produce the best results and by actually constructing physical models circuits containing such elements. By observing which circuits were the most effective and which circuit operations were practical, the team began to develop a more specific and detailed circuit design.

Build a Prototype

The prototype that was decided on was a combination of all of the original models. The final prototype can be seen in the *Prototype Specification* section of this report.

Test and Redesign

This final step was perhaps one of the most important and resilient steps in the process. After countless hours of persistence and redesign, the final circuit was decided on as shown in the *Proof of Design* section of this report. The redesigns were primarily based on the practicality of each function in the circuit. If the circuit contained a function that was not essential or was not consistent with the constraints defined for the project, the team would undertake a complete redesign of the circuit in order to maximize its functionality.

By using this industry proven engineering design process, the final circuit design was finalized and documented. The final design did incorporate all the functions listed in the *Design Objectives* in a very efficient and practical manner while ensuring user safety was kept the number one priority.

Upon further analysis of the design after the circuit was completed and operating correctly, the team discovered a very important implication of the design. As mentioned in the *Physical Implementation* section of this report, the team discovered that this design solution could be extended for use in literally any type of application that requires a negative feedback loop dependant on temperature. This means the design can be used for any application that requires an electrical device to be turned off or turned on at a certain temperature in any environment. This remarkable realization demonstrates the nearly limitless possibilities for the application of this circuit. The circuit’s simple and intuitive design allow it to be implemented in any type of situation or environment as an effective and safe low-cost solution capable of meeting any heating or cooling demands.

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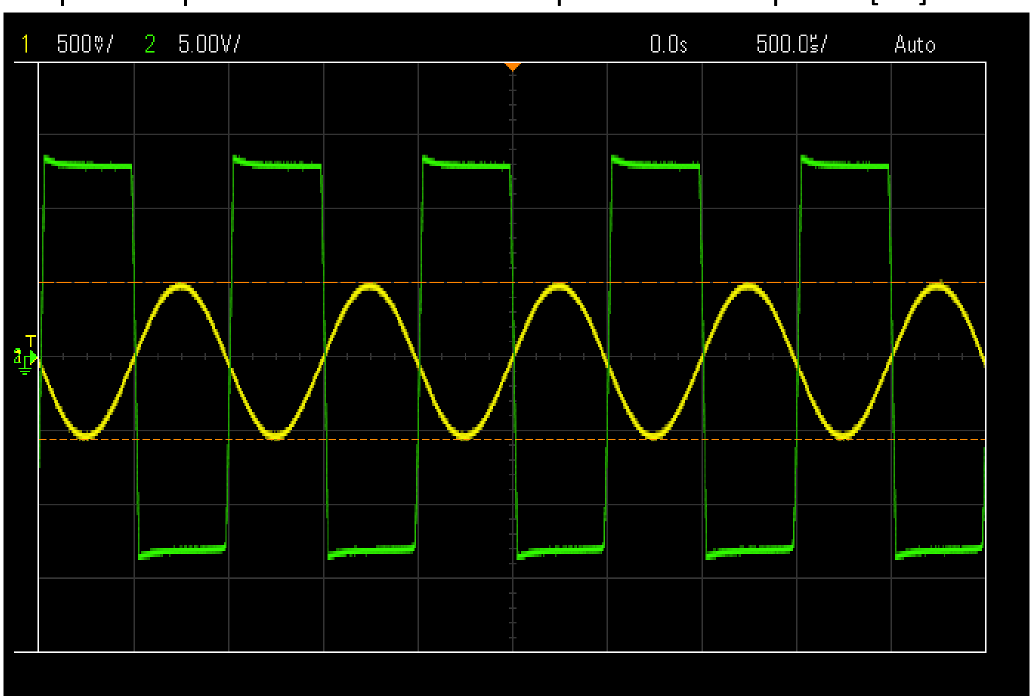
Appendix

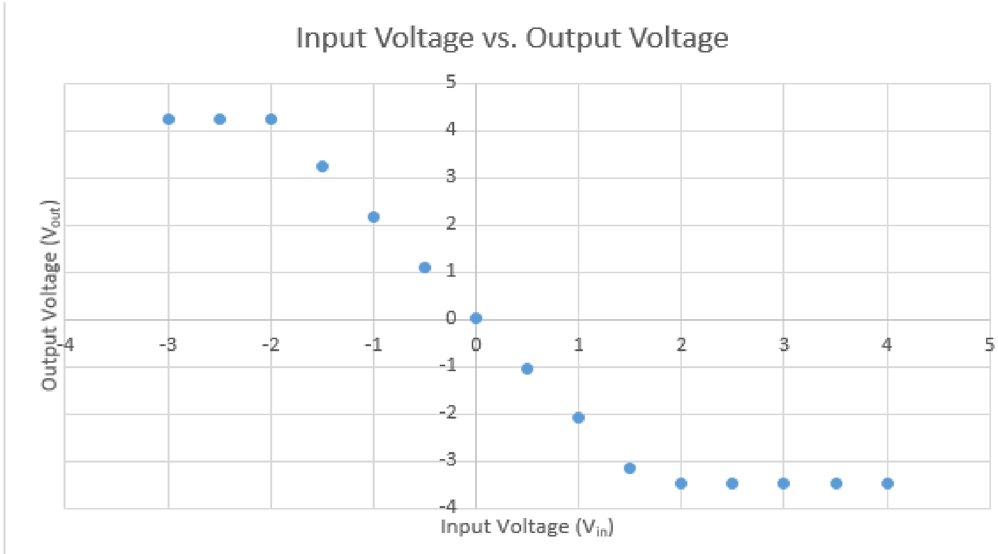
A. Operation of Saturated LM741 Op-Amp

Input		Output
Non-Inverting Terminal	Inverting Terminal	
High	Low	High
Low	High	Low

B. Graphical Operation of the LM741 Operational Amplifier [11]



C. Difference Operational Amplifier



D. Operation of the LM335 Temperature Sensor