Thermoelectric Water Bottle Cooling Station

A Technical Report submitted to the Department of Computer & Electrical Engineering

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In Partial Fulfillment of the Requirements for the
Degree Bachelor of Science in Engineering

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Signature ____ Date __________

Approved ____ Date __________
Harry Powell, Department of Computer & Electrical Engineering

Abstract

Black Apple’s Electronic Water Bottle Cooling Station is a device that will be used to cool a bottle filled with water down to a temperature of 40°F. The project entails designing and building a portable cooling station that will cool the water inside the water bottle to the specified temperature. The core features of this device include a thermoelectric cooler with a heatsink which will displace the heat from the water inside the water bottle along with a fan and vents to properly dissipate heat. The Peltier module and fan will interact with a MSP430 and temperature sensors to control cooling and track the temperature of the water.

Background

The majority of people find a cold bottle of water more refreshing than a warm bottle of water. However, a major inconvenience for carrying around a water bottle is that over time the water inside the water bottle warms up due to external temperature. Thus, unless there is a refrigerator nearby it is impossible to cool the water back down, and oftentimes the water will be dumped out and wasted as it is no longer considered to be drinkable.

[1] One of the most common causes of water waste in households is for people waiting for tap water from the faucet to turn cold. A standard faucet installed in the 1990’s flows at a little over 2 gallons of water per minute [2], meaning if it takes just 15 seconds for the tap water in the faucet to become cool then over half a gallon of water will be wasted for just one glass of water. Water Bottle Cooling Station will help address this water waste issue by simply allowing anyone to place their water bottle into the device and cooling process will be a self contained process.

There was a device named the Self-Chilling Can designed in 2000 which utilized vacuum heat pump technology [3]. The vacuum pump would extract heat from the water and displace it into a heat sink. With this method, the Self-Chilling Can was capable of cooling water down to 30 °F in just a few minutes.

Today, there does not exist a self cooling water bottle or a similar cooling station mechanism available commercially, the closest device to a self cooling water bottle that is available are insulating water bottles that are able to keep water at a certain temperature for a long duration of time. [4] Additionally, there exist thermoelectric coolers commercially, however these devices are much larger in scale than what would be the Water Bottle Cooling Station designed by our team.

There currently does not exist a product such as the Water Bottle Cooling Station on the market. What distinguishes the Water Bottle Cooling Station from any device is that unlike other similar devices that already exist, the Water Bottle Cooling station will be able to cool water down and not just keep it at a certain temperature. Additionally, unlike a thermoelectric cooler, the Water Bottle Cooling Station will be designed to service just a single water bottle and thus would be more of a convenience utility that could be used on office desks or other similar situations.

Lastly, the Water Bottle Cooling Station differentiates itself from the previously existing Self-Chilling Can by its method of cooling water. The Water Bottle Cooling Station will utilize thermoelectric technology to cool water while the Self-Chilling Can uses a vacuum heat pump. Unlike the Self-Chilling Can, the Water Bottle Cooling Station will also provide an interface to set a desired temperature to control the amount of cooling.

Some elements of our engineering curriculum is featured in this project including: embedded and hardware design, CAD, and thermoelectric cooling. All team members have some experience with embedded programming along with hardware design. Micah Harris has experience with CAD, while no member on our team had any significant experience with thermoelectric cooling.

Constraints

Design Constraints

There were many design constraints with regard to the PCB design. First, the voltage regulators and switches along with their accompanying parts had to be selected so that they could be readily simulated. This meant that they either had to be in the Texas Instruments database for the Webench power designer, in the National Instruments database for Multisim, or it had to have a SPICE model available. Furthermore, the accompanying components had to either be in our FUN lab kit or present on digikey or a similar website. If the component was being purchased, then the speed of delivery had to be considered as well. Finally, the PCB layout had restrictions due to the manufacturer limitations for a board that fit our timeline. This resulted in two predominant constraints: a 2-layer board instead of a 4-layer board was used and the copper thickness was only 1 oz/ft^2. Since our board had high current requirements, the trace widths were constructed to be wide and short to handle current and heat requirements, respectively. The resistance and power loss also had to be considered for the trace widths.

Economic and Cost Constraints

In the original CAD design, the initial height of the container was designed to be 10 inches, however was scaled down to 6 inches and the thickness of the insulating walls were also halved to 1.5 mm. These scale backs were a result of the initial CAD design being too costly so these changes needed to be implemented in order for the container to be more cost efficient

External Standards

Given the device's design of having electrical components in close proximity with water, [5] NEMA standard 2, 12, or 13 were implemented for the cooling system and MSP430 enclosures. Since the device is powered using an electrical outlet, the standards of electrical power in the United States were taken into consideration for the design: 60 Hz, 120 V.

Also standards are in place for equipment used for the transport and consumption of water. These standards are [6] NSF/ANSI 51 which establish public health and sanitation requirements for materials used in the construction of commercial food equipment, and NSF/ANSI 61 which establish the minimum health effects requirements for the chemical contaminants and impurities that are indirectly imparted to drinking water from products, components and materials used with drinking water.

Additionally, standards for PCB design were considered, specifically [7] IPC-2221B which are the generic standards on printed board designs and IPC-2152 which are the standards for determining current carrying capacity in printed board design. Lastly, [8] NFPA 70, which are standards for safe electrical design, installation, and inspection to protect people and property from electrical hazards were also considered.

Tools Employed

Solidworks was a new Computer-Aided Design and 3D Modeling technology Robin and Micah had to learn. It was used to create the container and ensure a proper fit between the heatsink and fan units within it before the final draft of the container was produced.

National Instruments (NI)' Multisim, a circuit simulation and design software, was used to create a two dimensional layout for our circuit board. The sketch was exported to NI's Ultiboard to create a three dimensional model that would be the final design phase before printing a draft. Both technologies were relearned and primarily used by Mac and Everett.

Texas Instruments' Webench Power Design tool was used to simulate the effects of the voltage regulators on the circuit board schematic.

A PCB trace width calculator resource from Advanced Circuits was used to determine an appropriate trace width and resulting power loss given a trace thickness and trace length.

FreeFDM also by Advanced Circuits was used to test the PCB layout for any routing errors, or possible manufacturing requirement infringements.

A Hewlett-Packard Power Supply was used to provide power to our thermoelectric cooler, heatsink, and fan before the circuit board and accompanying power cords for our project were designed and functional.

TMP36 sensors were programmed by EJ to automate the temperature-checking process for our system. EJ programmed the sensors in the C programming language via Code Composer Studio. He improved his skills coding in C while also learning how to specifically program the MSP430 sensors for the first time.

Robin used a dremel to customize the aluminum plate that heads our cooling station. The dremel was used to cut the plate down into a square piece; Robin also used a drill to counterbore four holes into the plate that were compatible with the screws on the thermoelectric cooling unit.

A Weller Soldering Iron was used by the team to install components on to the circuit boards for testing and implementation.

Robin and Micah used SmartSheet and GanttProject to produce and reproduce the Gantt Chart timelines throughout the Capstone semester.

Ethical, Social, and Economic Concerns

Environmental Impact and Sustainability

One concern we have is that our device will be electrical consumption given the fact that the device will be powered using electrical outlets. The anticipated energy consumption impact is small, but still something to consider since we are making the simple process of drinking water now part of the energy grid.

Even the most modern thermoelectric cooling devices are wildly inefficient offering around 1/4th (10 - 15 %) of the efficiency of conventional cooling methods (40 - 60 %). Therefore, the device will need to be carefully designed to ensure that the water is being cooled as effectively as possible so that it does not take too long to cool. Additionally, since the cooling system will not be in direct contact with the water, the cooling process will take even longer since the cooling system will need to cool the water through a physical barrier. With all this considered, optimizing our cooling system to be as efficient as possible was a top priority.

One benefit the product contributes to the environment is reducing water waste. A very overlooked contributor to water waste is individuals throwing out warm water or waiting for tap water from the sink to cool down to a desirable drinking temperature. A kitchen sink from the 1990’s on average dispenses about 2 gallons of water per minute, so instead of waiting for the water in the running sink to cool down, it would be more efficient to cool warm water down with the Water Bottle Cooling Station.

Health and Safety

A big issue that will be needed to figure out is how will the Water Bottle Cooling Station be able to effectively and safely transfer the heat from the water inside the bottle to the outside. This entails making sure that the fan, vent, and heat sink we use will be able to properly accommodate the heat dissipation from the cooling system. Given all the heat dissipation from the cooling system, the ventilation system needs to be able to function well enough so the overall device does not overheat and pose any threat to the user.

Given that the device will be used for drinking water, standards must be followed so that the device properly conceals components that are susceptible to water damage such as the temperature probe. Additionally, these components need to be concealed so that the Water Bottle Cooling Station can be properly cleaned to prevent mold or other substance build up that could contaminate the drinking water.

Manufacturability

The design of the cooling station must be small enough such that it will be able to be compatible with a standard 16.9 fl oz water bottle. Also, given all the components needed to design and build the Water Bottle Cooling Station, it needs to be designed such that it is cheap enough for someone to consider purchasing it, however, since this product will be viewed more as a luxury good we acknowledge that only people with disposable income would ever consider purchasing this product.

And additionally, it also needs to be durable enough for practical use meaning that it should be designed such that the cooling system and other components inside are not easily damaged from outside contact or from water damage from the water bottle. So the physical packaging that will be responsible for encasing the entirety of the cooling system needs to be strong enough to support the water bottle, while also not being flammable in the case that the cooling system overheats, but will also still allow the cooling system to efficiently cool the water down.

Ethical Issues

One ethical issue to consider is that the Water Bottle Cooling Station is not actually solving a necessity, but instead providing convenience to a luxury. There exists no health concerns resulting from drinking warm water, and in some other cultures around the world, drinking warm water is actually the preference over drinking cold water. So designing a cooling station for a water bottle is not actually the most environmentally conscious resolution to the problem and actually is instead promoting a consumerist culture reliant on convenience and luxury.

Intellectual Property Issues

One similar US patented product is the self-chilling can, InterBev 2000, mentioned in the background section. This device utilizes the latest thermal and vacuum heat pump technology. The manufacturing company claims that the can is capable of a minimum temperature of just 30˚F, which it reaches it just minutes.

Another similar product is the SpinChill beverage cooler [9]. The SpinChill attaches to the top of a can, and rotates the can vertically very quickly. This motion exerts a centrifugal force on the beverage, pushing the warm liquid in the center of the can to the walls where it is then dissipated.

While these are impressive products, our design avoids patent infringement because it utilizes an entirely different cooling method in thermoelectric cooling via the Peltier effect.

Detailed Technical Description of Project

The Water Bottle Cooling Station is a portable device that allows the user to actively cool water on the go. The cooling station consists of 4 main parts: a power supply, a printed circuit board (PCB), a thermoelectric cooler, and the container for the cooling station. The power supply is connected to the PCB and is the source of power for all major components. These components are the MSP430G2553[10], voltage regulators, bridges[11], temperature probes[12], and an LED[13]. The fan and Peltier Module of the thermoelectric cooler are also powered by the power from the PCB. Other PCB details are explained later. The thermoelectric cooler is connected to, and controlled by, the MSP430G2553. The cooler is made up of an aluminum plate[14], a Peltier Module[15], a heat sink[16], and a fan[17]. The module was placed onto the heat sink using thermal paste[18]. The cooler rests inside of hollow pegs on the bottom of the container. There are two temperature probes. One is pressed to a piece of urethane foam[19] that is attached to the side of the water bottle and the other rests inside of the heat sink.

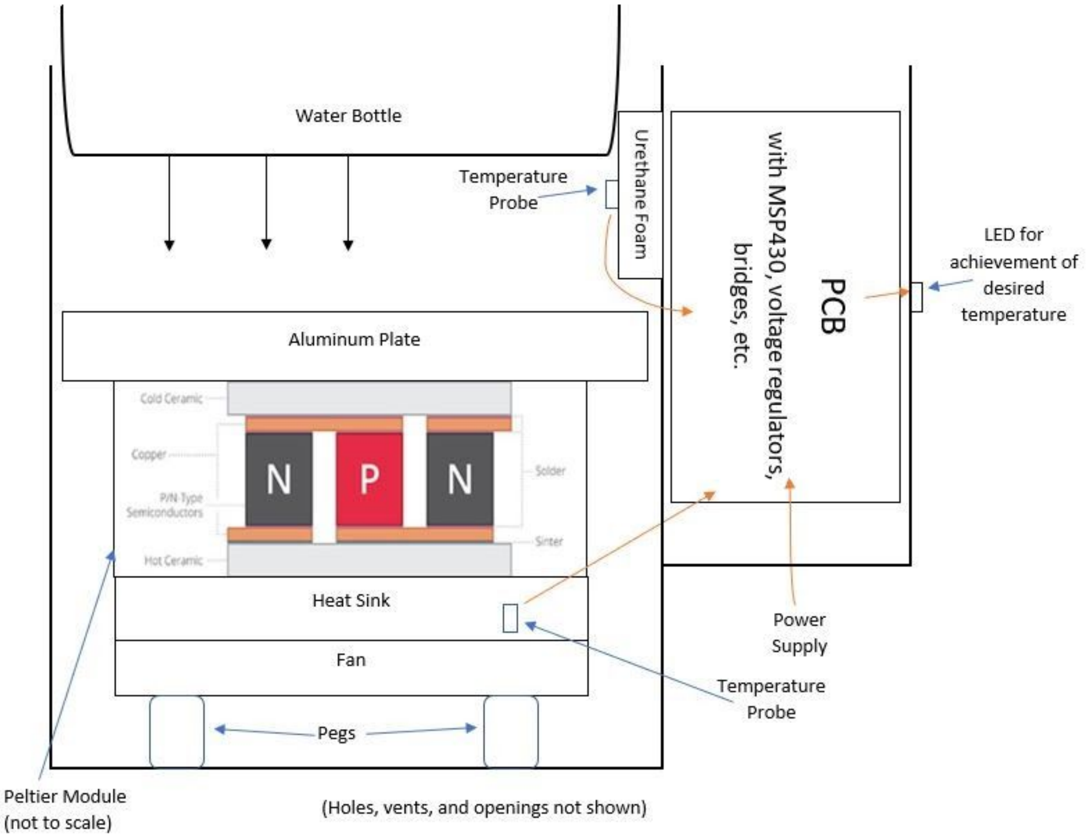


Figure 1 General Overview of Water Bottle Cooling Station

The actual cooling of the water is done using the thermoelectric cooler. The MSP430G2553 controls current to the cooler to allow the Peltier Effect to take place. The Peltier Effect is achieved by applying an electrical current at the seam of two materials and having the current give or absorb heat. In our case, we are absorbing heat, as we want to cool the water to a certain temperature. The way that the Peltier Effect works, if we want the side of the cooler that is touching the water bottle to be cold, then the other side of the cooler will be hot. Because of this, a heat sink is connected to the hot side and helps to disperse the heat as well as a fan to blow the hot air out. We also have vents in the sides and bottom of the cooling station container to allow for proper airflow.

The process starts with the power supply[20] being connected to a wall outlet using a power cord[21]. The 120V will go into the power supply and be converted to 15V. This 15V will then go into a 4 places: the peltier module, a 15V-to-12V voltage regulator[22], a 15V-to-3.3V voltage regulator[23], and a bridge. When the device is initially plugged in, both the peltier module and fan receive current. The peltier module is connected to 15V on the positive terminal and the output of a bridge on the negative terminal. The bridge is also connected to the MSP430G2553. This allows for the MSP430G2553 to control whether current is being provided to the module or not, essentially controlling the module. If the MSP430G2553 pin that the bridge is connected to is off, the output of the bridge will be connected to ground and current is allowed to flow through the module. On the other hand, if the pin is on, then the output of the bridge will have 15V. Because this bridge is connected to the module and the module has 15V at the positive terminal, no current will flow through the peltier module and the module will be off, in a sense. The determining factor of if the module is on or off is whether the water in the water bottle is above or below a certain temperature. The module is initially on, so the code programmed to the MSP430G2553 continually checks if the temperature probe is reading a temperature at or below 40°F. If the answer is no, then the module stays on. Otherwise, the MSP430G2553 turns off the specified pin and the peltier module shuts off.

A similar process was implemented with the fan of the thermoelectric cooler. The positive terminal of the fan is connected to the 12V output of a voltage regulator and the negative terminal is connected to the output of a bridge. The determining factor of the fan being on or off is the temperature of the heat sink. The MSP430G2553 continually checks if the heat sink temperature probe is reading a temperature below or equal to 95°F or above or equal to 113°F. If the latter, the fan stays/turns on. Otherwise, the MSP430G2553 turns off the pin connected to the fan's bridge and the fan shuts off. The opposite is true for the other case. If the temperature is in between, then the fan stays/turns on as there is no harm done if the heat sink gets too cold, but it is dangerous for it to be too hot. The purpose of turning on and off the fan is that we do not want the heat sink to be too hot as that could be a hazard and have negative effects on the container, but we also do not want the heat sink to be too cold as we want to take full advantage of the

Peltier Effect. Besides the temperature probes and bridges, the MSP430G2553 controls the LED that indicates whether the water has reached the specified temperature. Both the Peltier Module and Fan Logic are shown later in the paper.

The full process of how the Water Bottle Cooling Station works is the power supply is connected to a wall outlet providing power to the PCB and the fan and Peltier Module are turned on. If there is no water bottle in the container, the water temperature probe will read from the air in the container and will turn the module off if the air temperature is below 40°F degrees as that is the threshold and there is no water bottle in place. Because the heat sink starts off relatively cool, the fan turns off once the temperature from the heat sink temperature probe is read, but turns back on as the heat sink pulls heat from the Peltier Module. Once a water bottle is placed in the container and the water bottle temperature probe makes contact with the water bottle, the temperature probe will send the data to the MSP430G2553 which will make a determination on whether to keep the module on or turn it off. Assuming the module stays on, it will continue to do so until the water bottle temperature probe reads a temperature below 40°F. When this occurs, the module will shut off and the LED to indicate that the water is sufficiently cooled turns on. All the while, the MSP430G2553 is running the check for the fan and turning it on and off based on the heatsink temperature probe's readings.

The container of the cooling system was 3D printed using plastic filament. It is made with X, Y, Z dimensions of 80, 135, and 125 mm, respectively. It includes an 80 by 80 mm primary ventilation compartment of height 135 mm with walls of width 1.5mm. Connected to one side of the primary ventilation compartment is a compartment for the board to be stored, including a rectangular throughhole connecting the primary box with the holding box and a rectangular hole at the bottom of the holding box for any wires that may need to be connected. All of the other sides of the container are covered with ventilation holes as shown below. We chose to do our temperature change calculations based on a glass water bottle. Since many of the water bottles we see people use are made of glass, we wanted to test a bottle made out of that material. We need to calculate how measuring the temperature through the glass will affect our reading. Because a water bottle goes into the cooling station, we do not anticipate the station needing cleaning outside of being wiped down with a damp cloth.

Figure 2 Container - Bird's Eye View

Figure 3 Container - Side View

Figure 4 Container - Corner View

The schematic used for this thermoelectric cooler consisted of the power supplies and switches to each of the components: peltier module, fan, half bridge driver switches, voltage regulators, temperature probes and the MSP430.

In order to power the fan, a voltage regulator was needed to change the incoming voltage from 15V to 12V, while also allowing a current of 1.6A. The regulator chosen was the LM2576T-12/NOPB-ND, a switching regulator to allow for the larger output current. The component design required an input and output capacitor, an inductor and a catch diode. The input capacitor is necessary to maintain stability and decrease incoming impedance to the voltage regulator. In order to have effective bypassing capability, a capacitor of at least 100uF must be chosen. The output capacitor is necessary to filter the output voltage. In order to do this effectively, it is best for the capacitor to have a high capacitance and low ripple voltage and, thus, a high voltage rating. A 1000uF capacitor with a 50V voltage rating was chosen. The inductor was chosen by using the data sheet for the voltage regulator. The data sheet provided a list of appropriate inductors and which one to use for more specific requirements. Since we are operating the switching regulator in continuous mode (the inductor current will never drop to 0A. The 100uH inductor chosen was dependent on both the regulator output voltage and the use of continuous mode. Finally, the catch diode is used to return the current from the inductor for when the regulator is switched off. Since we are not using this feature of the regulator, this component serves little purpose, but we still used a Schottky diode as recommended for high-efficiency and low voltage drop.

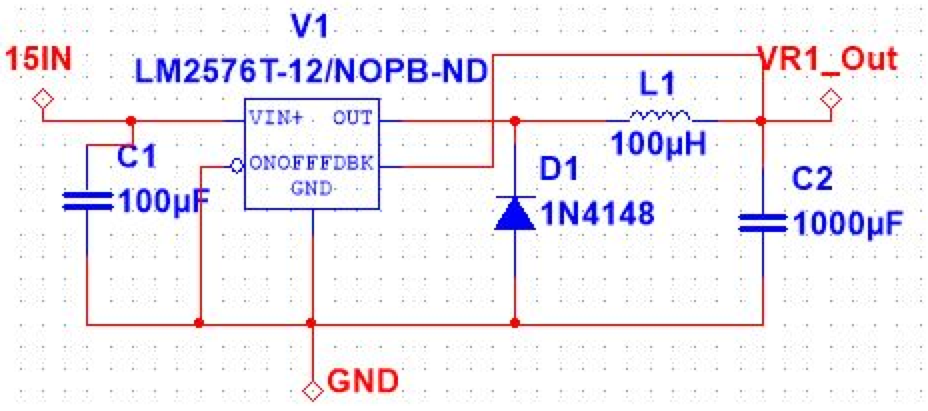


Figure 5 Voltage Regulator 1 (15V → 12V)

In order to power the temperature probes and MSP430, another voltage regulator was needed to convert the voltage from 15V down to 3.3V with very minimal current requirements (less than 500uA). Due to the low current requirement, a linear regulator was chosen (L78L33ACZ-AP). Since the regulator is a fixed 3.3V linear regulator, it is not very complex. All accompanying parts only consist of an input and output capacitor. These capacitors were chosen based off of recommendations in the data sheet, and then altered and confirmed using experimentation. In the end, two ceramic capacitors with the values of 0.33uF and 0.1uF were used for the input and output capacitors, respectively. The purposes of these capacitors are similar to those in the first voltage regulator: filtering voltages and maintaining stability.

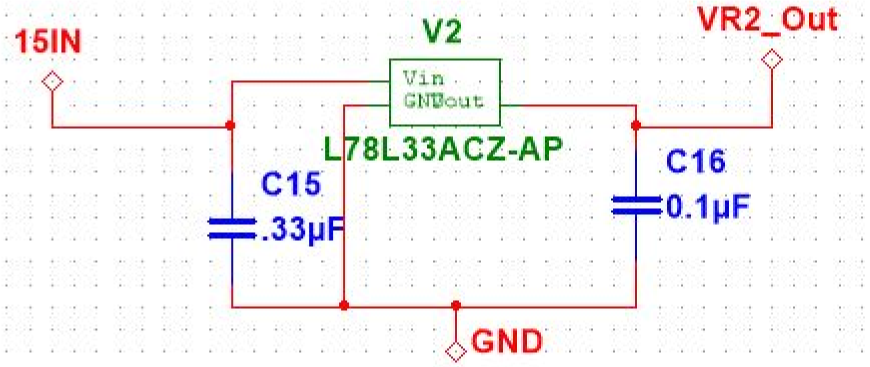


Figure 6 Voltage Regulator 2 (15V → 3.3V)

Finally, half bridge drivers were used as switches to power off and power on the peltier module and the fan (as explained earlier in this section). The half-bridge driver we selected was the BTN8982TAAUMA1. This is a 9-pin driver that contained a lot more functionality than we needed, so we attempted to keep the design as simple and similar to the data sheet as possible (also taking into account our limited exposure to h bridge drivers). Of the nine pins, many are input pins that can alter the behavior of the half bridge driver. These include the input inhibitor pin, which controls whether the switch or half bridge driver is on or off. This was the primary input pin that we cared about. Other pins include the IN pin, which controlled the polarity of the output voltage, the slew rate pin, which controlled the rate at which the voltage changed when switched off or on and the current sense pin, which evaluated the status of the output.

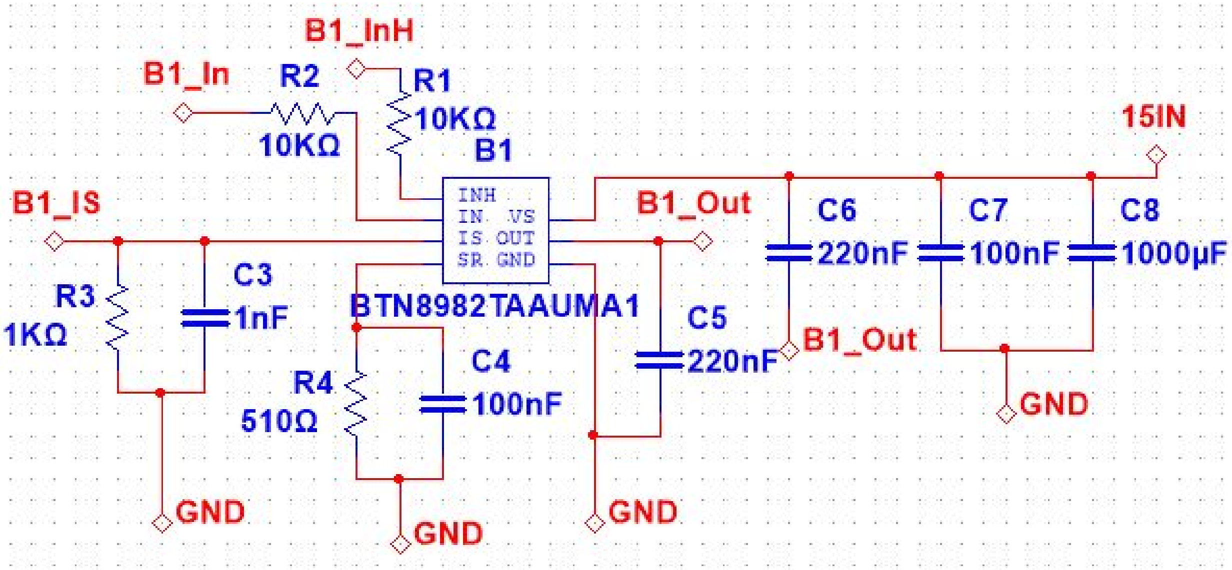


Figure 7 Half Bridge Driver used as Switch

In order to assemble the board properly, many factors had to be considered to maintain stability, temperature change, and current requirements. The first thing to consider is, generally, most basic electronic components (mainly capacitors, inductors and diodes) need to be placed near their mother component. Furthermore, this task was usually directed on the data sheet. The first voltage regulator (15V → 12V) required the input and output capacitors, inductor and diode be placed near the regulator. The diode's needs were valued less, because we were not interested in using the on/off capability of the voltage regulator. This trend was consistent for both the other voltage regulator and the half bridge drivers. Another thing to consider was spacing out the more temperature variant components to distribute the heat across the board. These components consisted of the h bridge drivers, then the linear regulator and the switching regulator. The trace widths also needed attention due to the high power requirements of the thermoelectric cooler. The power and ground trace widths were widened to 100 mils to account for the 10A of current. They were also made as short as possible to decrease the temperature change. These calculations were done using a trace width calculator. Finally, we used the online resource FreeDFM to check for any routing or via issues within the board.

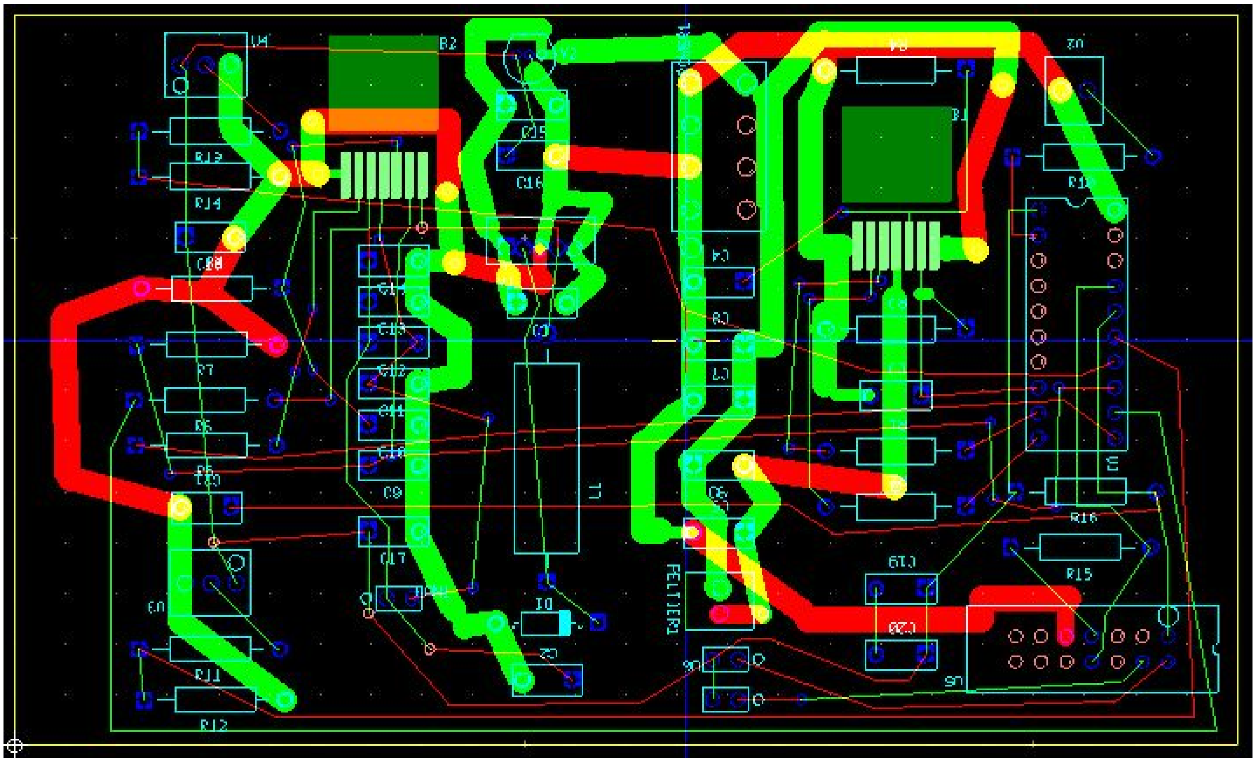
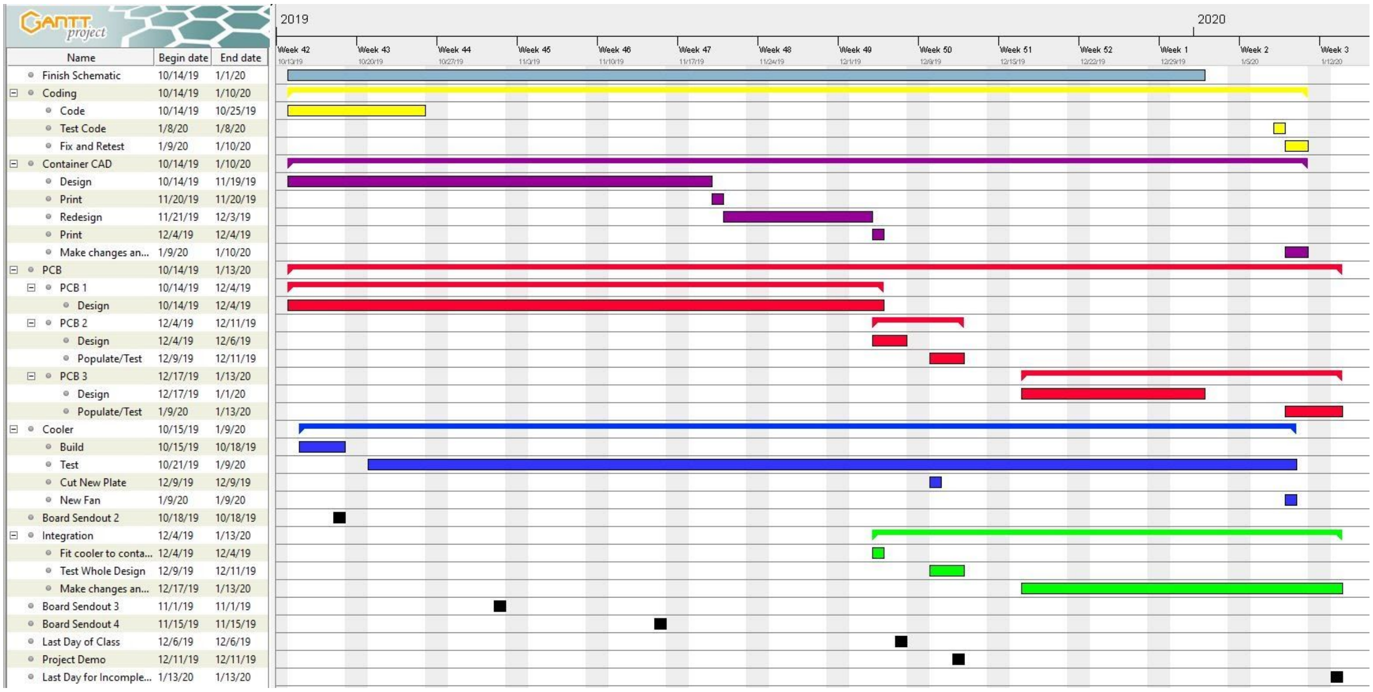


Figure 8 Printed Circuit Board Layout

Project Timeline



Name	Begin date	End date
Finish Schematic	10/14/19	1/1/20
Coding	10/14/19	1/10/20
Code	10/14/19	10/25/19
Test Code	1/8/20	1/8/20
Fix and Retest	1/9/20	1/10/20
Container CAD	10/14/19	1/10/20
Design	10/14/19	11/19/19
Print	11/20/19	11/20/19
Redesign	11/21/19	12/3/19
Print	12/4/19	12/4/19
Make changes an...	1/9/20	1/10/20
PCB	10/14/19	1/13/20
PCB 1	10/14/19	12/4/19
Design	10/14/19	12/4/19
PCB 2	12/4/19	12/11/19
Design	12/4/19	12/6/19
Populate/Test	12/9/19	12/11/19
PCB 3	12/17/19	1/13/20
Design	12/17/19	1/1/20
Populate/Test	1/9/20	1/13/20
Cooler	10/15/19	1/9/20
Build	10/15/19	10/18/19
Test	10/21/19	1/9/20
Cut New Plate	12/9/19	12/9/19
New Fan	1/9/20	1/9/20
Board Sendout 2	10/18/19	10/18/19
Integration	12/4/19	1/13/20
Fit cooler to conta...	12/4/19	12/4/19
Test Whole Design	12/9/19	12/11/19
Make changes an...	12/17/19	1/13/20
Board Sendout 3	11/1/19	11/1/19
Board Sendout 4	11/15/19	11/15/19
Last Day of Class	12/6/19	12/6/19
Project Demo	12/11/19	12/11/19
Last Day for Incomple...	1/13/20	1/13/20

Figure 9 Final Gantt Chart

We had no serial tasks. Everything was done in parallel.

Parallel tasks

- Weeks 42-44: Code->Test | CAD Design | PCB 1 Design | Cooler Build -> Test
- Weeks 44-49: CAD Design -> Print -> Redesign | PCB Design | Cooler Test
- Weeks 49-51: CAD Print | PCB Design -> Populate/Test | Cooler Test | Cooler fit -> Test Whole Design -> Make changes
- Weeks 51(2019)-2 (2020): PCB 3 Design | Cooler Test | Integration Changes
- Weeks 2-3: Fit and Retest | Container CAD changes and integration | PCB 3 Populate/Test | New Fan | Integration Changes

Primary and secondary tasks:

Micah - Primary: CAD Design and Implementation

Robin - Primary: Designing and assembling thermoelectric cooler
Secondary: 3D CAD work

EJ - Primary: Embedded Coding
Secondary: PCB Schematic and Layout

Mac - Primary: PCB Schematic and Layout

Test Plan

Thermoelectric Cooler

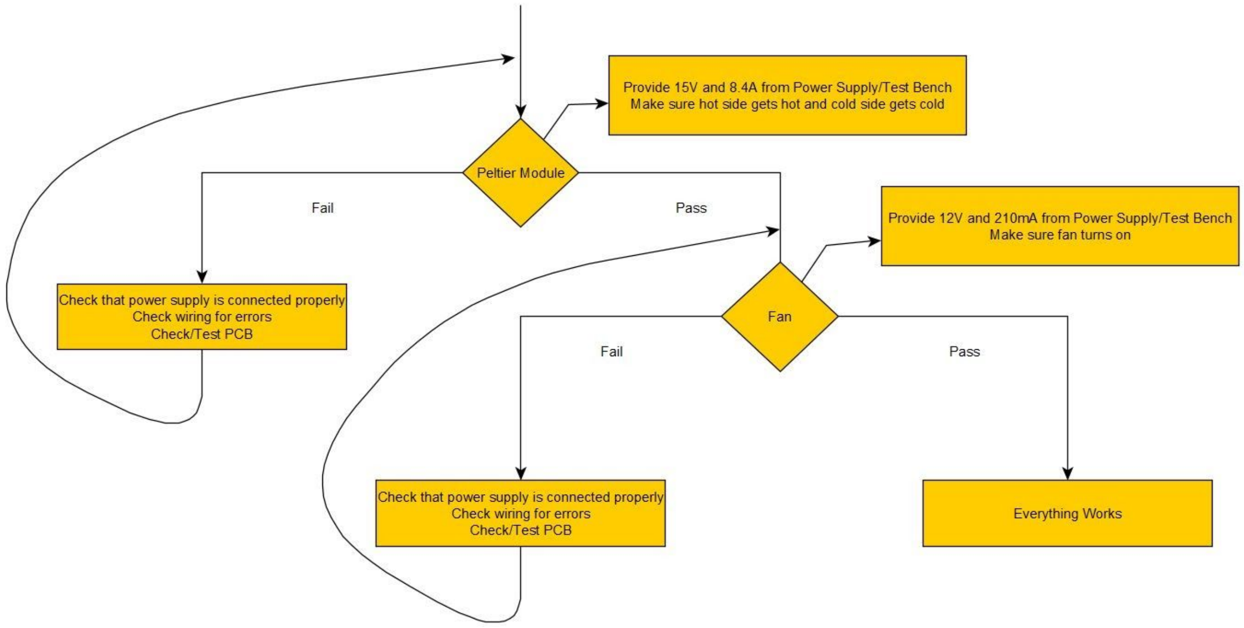


Figure 10 Thermoelectric Cooler Test Plan

Our initial design for the Peltier Module called for 8.4A, but we changed it 10A. We planned to test these full values, but the Virtual Bench we used could only supply 1A max. Even the power supply that we found to test with could only supply a max of 6A with a voltage range of 0V to 6V. Given this, we were not able to fully test the full capabilities of the Peltier Module without the PCB. Even so, when we provided what we could from the power supply, the module began to behave as we expected.

When we were able to test the Peltier Module with full power, we came across the issue of the cold side being overrun by the hot side. To fix this, we switched from our initial fan that had 30.4 CFM to a fan with 69.2 CFM to better aid in heat dissipation. We were able to provide the maximum power to the initial fan, but after the switch, we could only provide about 9V with our 1A limitations. We were ultimately not able to fully test the new fan with the heat sink.

Container

Initially, our guideline for designing and redesigning the container was to evolve it as we decided on specific parts for the heatsink, fan and thermoelectric cooler. After developing a final draft for submission, we learned that our build would be too expensive, leading to a thinning of the walls to 1.5 mm and a reduction in height of the container to 135 mm from 184 mm. The final design submitted for print is displayed below.

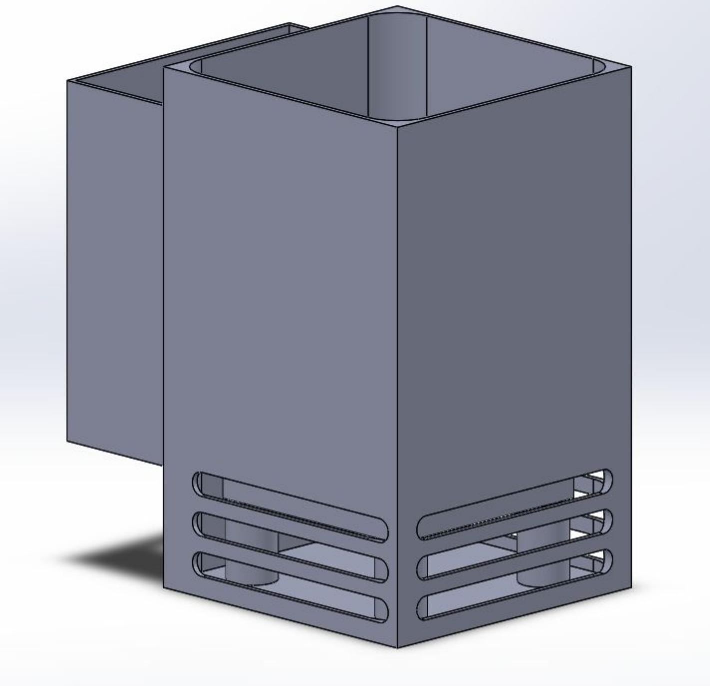


Figure 11 Final Container 3D Print Design

After the container was printed, we realized that we would need a bigger fan because the final print did not ventilate the heatsink and fan components sufficiently. We used a pipe cutter to manually cut vents above the previously printed vents, updating the design for the new, taller fan.

Figure 12 Container with Edited Ventilation

As shown above, there were two holes manually cut into each side where the three printed holes presided. These new holes increase ventilation of the container and were necessary as we did not have the resources or time to do another 3D print.

Code

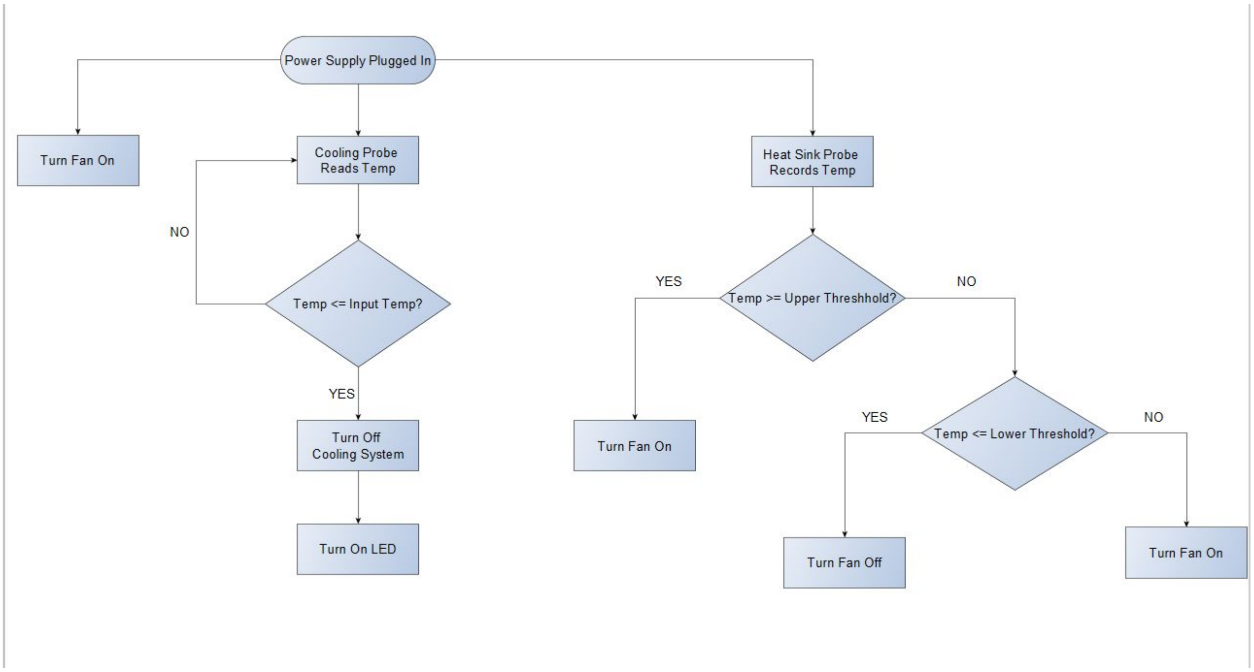


Figure 13 Software Design Flow Chart

A breadboard and MSP430 Launchpad were used to test the embedded design of the system. First, the code for the temperature sensors was tested by interfacing a TMP36 sensor with the MSP430 Launchpad and recording the outside temperature. Once the code for the temperature sensors was verified, the voltage switches were then tested with a VirtualBox and reading the outputs on the pins of the MSP430 Launchpad. No changed from the initial design were needed to be made for the software design due to testing.

Printed Circuit Board

The test plan for the printed circuit board remained pretty close to the original test plan. First, the voltage and current for the output of the power supply were verified to be 15V and 10A. The same measurements were done at each component that had the power supply input (the Peltier module, the two voltage regulators and the first half bridge driver) in order to verify that there was not a large power drop for each trace.

Next, the output for the first voltage regulator was tested for a voltage of 12V and 1.6A instead of the listed 300mA (we changed the fan to one that requires more current). The same measurement was also done at the input of the fan, the input of the second half bridge driver and the two temperature probes to once again verify that the trace did not result in a drastic power drop.

Following both of these tests, we strayed from the original test plan once more to verify the voltage and current exiting both of the half bridge driver switches. Ideally, the first switch would have an output identical or at least very similar to the power supply so as to eliminate the current running through the Peltier module when the switch is turned on. Similarly, the second switch should have had a voltage and current reading that closely resembles the first voltage regulator (12V and 1.6A).

Finally, the test plan stated that we test the outputs of the MSP430 to verify that each temperature probe, LED and switch has the proper incoming logic voltages. After completion of this step, all of the board could be evaluated together as a whole.

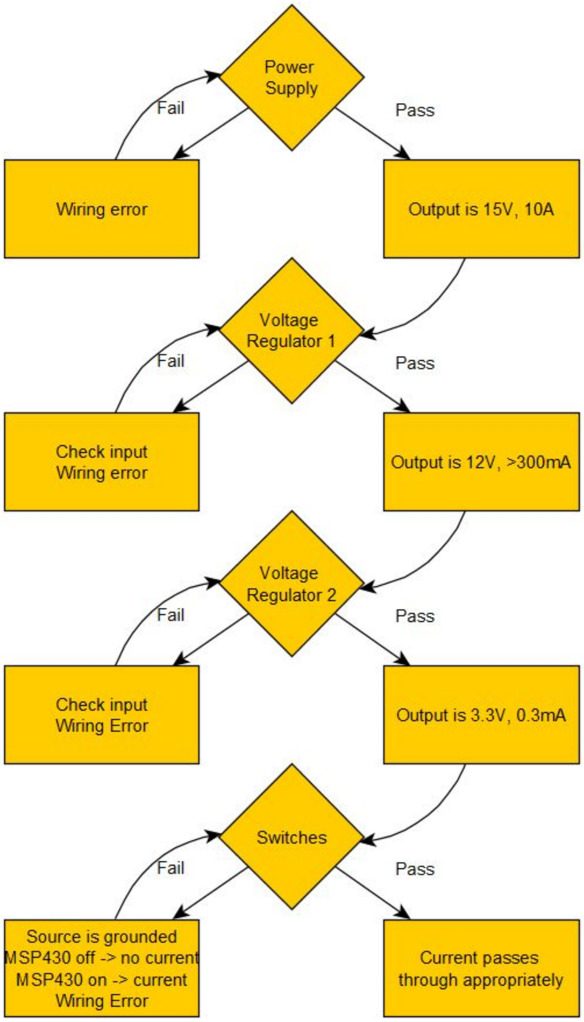


Figure 14 PCB Test Plan

Final Results

Given that we were unable to successfully develop a completely functioning PCB, we fell short of reaching any of the success criteria outlined initially in the original proposal. While testing, it was discovered that the bridge driver for the fan did not operate as we expected. Due to this, we were not able to get the fan working, which was essential in our cooling. We propose that we had a soldering problem as we saw decreasing voltage on the output of the bridge driver when we were expecting zero, but when we connected the fan we had a steady high output when we expected low. Alternatively, we could have had a bad bridge driver, as the behavior that we saw was not similar to any functioning operation that we anticipated from the datasheet, whether we had proper inputs or not. The output should have been steady high or low, but not decreasing.

Although we were able to supply power to the MSP430 microcontroller, we were not able to incorporate it because we did not have a functioning fan to control. Running only the Peltier Module would be dangerous as the fan is crucial to dissipating the heat. Given this, none of the functions from the embedded design were able to be incorporated into the final product, which included the TMP36 temperature sensors and the on/off switches for the Peltier Module, fan, or LED.

The Peltier Module and the fan function as expected when powered by an external source that is not the PCB, by making the cold side of the aluminum plate cool which was the bare minimum criteria crafted for the initial proposal. However, this criteria is not met when using the PCB as the system does not function at all from no power being supplied to the components.

Costs

We were able to keep our total costs under $250. Our most expensive item, at $40.19, was the .25-inch, 3x3 piece of aluminum that we bought for the thermoelectric cooler. A close second was the Peltier Module at $31.26. We were able to save costs on resistors and capacitors as we had most of what we needed on hand. The only thing that we were unable to account for was the container as we sent that in to get 3D printed and was not given the cost. If we were to manufacture in 10,000 unit quantities, the cost would be over 1 million dollars. Potentially buying one of each thing needed for the production would result in a cost of approximately $1,195,433. Because we used multiple of some items, buying 10,000 of every item, would not produce 10,000 of our product which is why the cost would be greater than the approximate 1.16 million.

Automated equipment would be beneficial for configuring/soldering components onto the PCB and cutting the aluminum plate to the proper size, but other than that automation would not save too much time or money. Automation is inherent in the making of the container, but putting the thermoelectric cooler only consists of pasting a Peltier Module onto a heat sink, layering an aluminum plate on top of a module on top of a heat sink on top of a fan and using 3 washers, a screw, and a nut to hold it all together. Such a task only takes about 10 minutes and most likely would not be worth the effort of building a machine unless the cost and time needed to build the machine is less than the labor costs and time needed to have people put them together.

Future Work

In the future, the biggest improvements to the project would be reducing the size and power needed for the cooling station, therefore increasing its mobility. If the cooling station can be remote without a need to be connected to a wall, its functionality and viability expands beyond a domestic environment; it could be used for cooling water that was in a warm car all day or cooling water that had to be boiled in the wild for purifying purposes. The scope and impact of the cooling station expands with the expansion of its mobility.

There are a few pitfalls to beware of. The cooling station needs to properly vent the heatsink which is 100% necessary for safe use. Finding a small and efficient fan and battery will help accomplish the goal of making the cooling station remote.

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Appendix

Black Apple	1	CUI Device	CP105433H	102-4697-ND	74	https://www.digik	31.26	261.072	Peltier Module
Black Apple	1	Advanced Therm	ATS-1146-C1-R0	ATS1506-ND	8	https://www.digik	16.63	117,825.40	Heat Sink
Black Apple	1	Wakefield-Vette	BT-301-50M	345-1552-ND	196	https://www.digik	12.46	86,520	Thermal Paste
Black Apple	2	Analog Devices I	TMP36GT9Z	TMP36GT9Z-ND	9,506	https://www.digik	2.96	7000	Temperature Probe
Black Apple	1	Texas Instrument	MSP430G2553IN2	296-28429-5-ND	3,575	https://www.digik	2.69	11,843	MSP430G2553IN20
Black Apple	1	Molex	22284020	WM50014-02-ND	32,029	https://www.digik	0.24	565.4	2-position Header
Black Apple	1	On Shore Technc	ED20DT	ED3054-5-ND	3,954	https://www.digikey	0.26	1,056	20-position Connector
Black Apple	2	Infineon Technol	BTN8982TAAUMA	BTN8982TAAUMA	13,874	https://www.digik	10.62	32,035.60	Bridge Driver
Black Apple	2	Molex	39281083	WM3803-ND	10,375	https://www.digik	1.29	5,919	8-position Mini-Fit Jr. Connector
Black Apple	1	XP Power	VES180PS15	1470-VES180PS1	29	https://www.digik	74	621,601	Power Supply
Black Apple	1	Qualtek	312019-01	Q353-ND	1,313	https://www.digik	11.06	66,889.20	Power Supply Cord
Black Apple	1			9057K175	N/A	https://www.mcm	40.19	401.9	Aluminum Plate
Black Apple	1			86195K83	N/A	https://www.mcm	14.84	148,400	Urethane Foam
Black Apple	2	TE Connectivity	282837-2	A113320-ND	133,280	https://www.digik	2.08	10,400	2-position Screw Terminal
Black Apple	2	TE Connectivity	282837-3	A113321-ND	120,645	https://www.digik	2.36	11,800	3-position Screw Terminal
Black Apple	1	On Shore Technc	302-S141	ED10522-ND	22,081	https://www.digik	0.32	29,632	14-position Connector
Black Apple	1	Mechatronics Fa	MQ6038E12B-FSF	1570-1137-ND	51	https://www.digik	14.53	14,530	Fan
Black Apple	1	Texas Instrument	LM2576T-12/NOPI	LM2576T-12/NOPI	3,881	https://www.digik	2.77	27,700	15V-to-12V Voltage Regulator
Black Apple	1	STMicroelectroni	L78L33ACZ-AP	497-16175-1-ND	8,845	https://www.digik	0.37	1,053.70	15V-to-3.3V Voltage Regulator
							240.93	1195432.772	

Figure 15 Final Costs and Estimates