The Solar Cooler

Team#7

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1. Introduction

1.1 Objective

During the summer, people usually bring a cooler for long drives or picnics to make their drinks stay cool, but the functionality of the cooler is highly depended on how often you can replace the ice. When the ice melts, the cooler just becomes a box filled with water. People has to lift their cooler, despite the weight of the water, box and drink, pour the warm water out and replace with ice. The situation might be worse if you are going for a picnic. The sun just melts the ice much more quickly and even worse, it is very likely that you can't find a store to buy more ice, and you are forced to have a hot coke in the summer.

The project goal is to develop a cooler that actively cools the items within via solar power, also, store energy to be able to cool the interior without sunlight presence.

The idea and need for a solar powered cooler is simple: we reduce the weight of the typical cooler and ice, and can increase the amount of time the objects within the cooler are cooled for and increasing space within the cooler. Using a solar panel to power the system is the most optimal way to do so, since it is lightweight and can charge the battery (or power the system) so long as there is incident light onto the panel's surface.

1.2 Background

The cooler is a very common appliance. The products on the market today is usually made with polyurethane insulation or vacuum insulation, both are very good insulation material, but they have one flaw in common: they can only absorb heat through the use of ice, the cooler itself doesn't have the ability of removing heat. We plan to improve this product by replacing the ice with a thermoelectric cooling pad which is a more lightweight cooling agent, and power it with sustainable green energy: the solar power. The cooler is designed to be easy to use, anybody who can use a traditional cooler should be able to use our solar cooler,providing the user with a simple yet effective solution to heavy and ineffective traditional coolers.

1.3 High-level requirement list

- Must cool at least 20°C below ambient temperature (to a minimum of 0°C).
- Battery life must be able to power the system independently for at least 2 hours.
- The weight of the system must not exceed 10kg, the lighter the better!

2. Design

2.1 Block Diagram

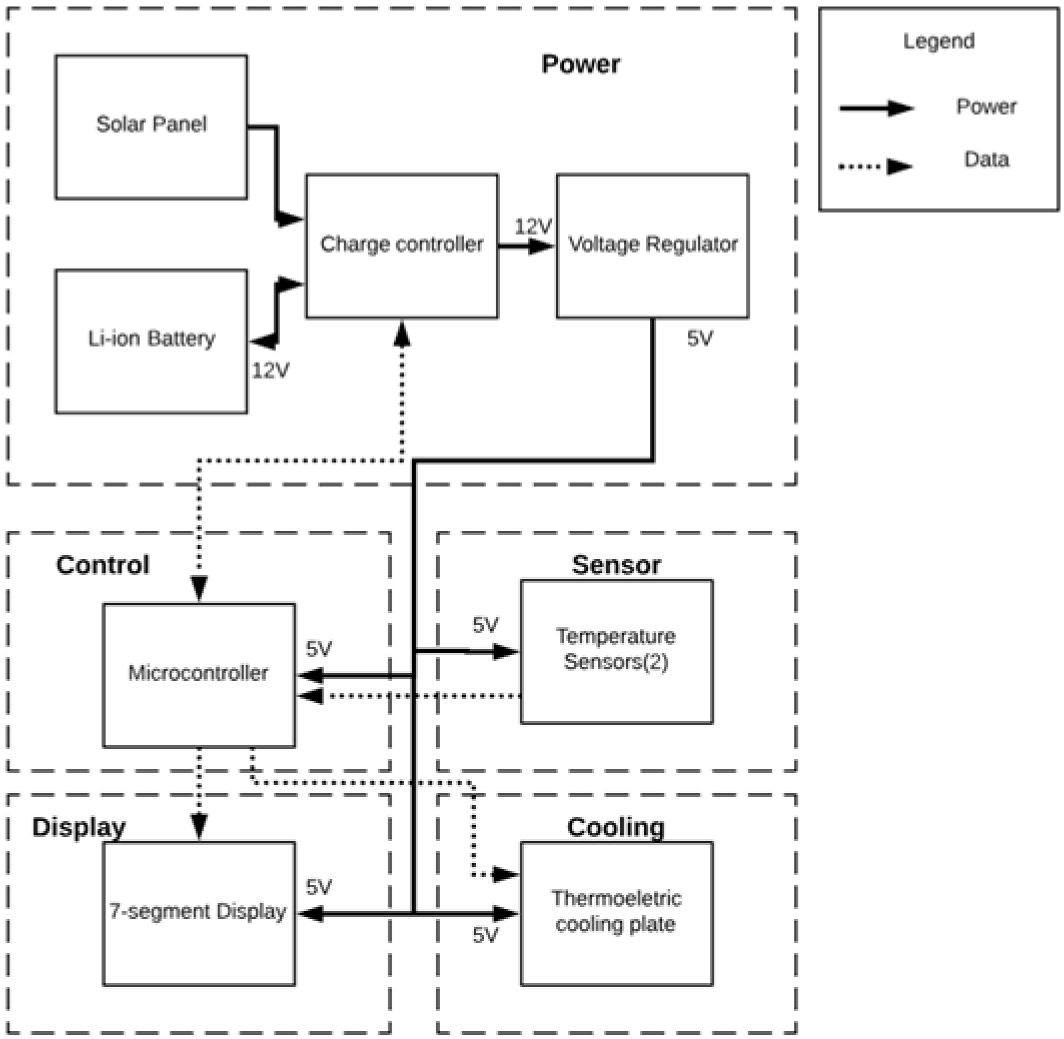

Figure 1: High Level Diagram

As the Figure 1 shows, the microcontroller will control the thermoelectric cooling plate according to the temperature sensors placed inside the cooler. The charge controller will manage the charge and discharge cycle of the battery and handle the power supply by the solar panel. The charge controller will provide the power from the Li-ion battery to the voltage regulator, which provides constant voltages to rest of the system. The charge status of the battery will be monitored by the charge controller and the data will also be send back to the microcontroller.

2.2 Physical Design

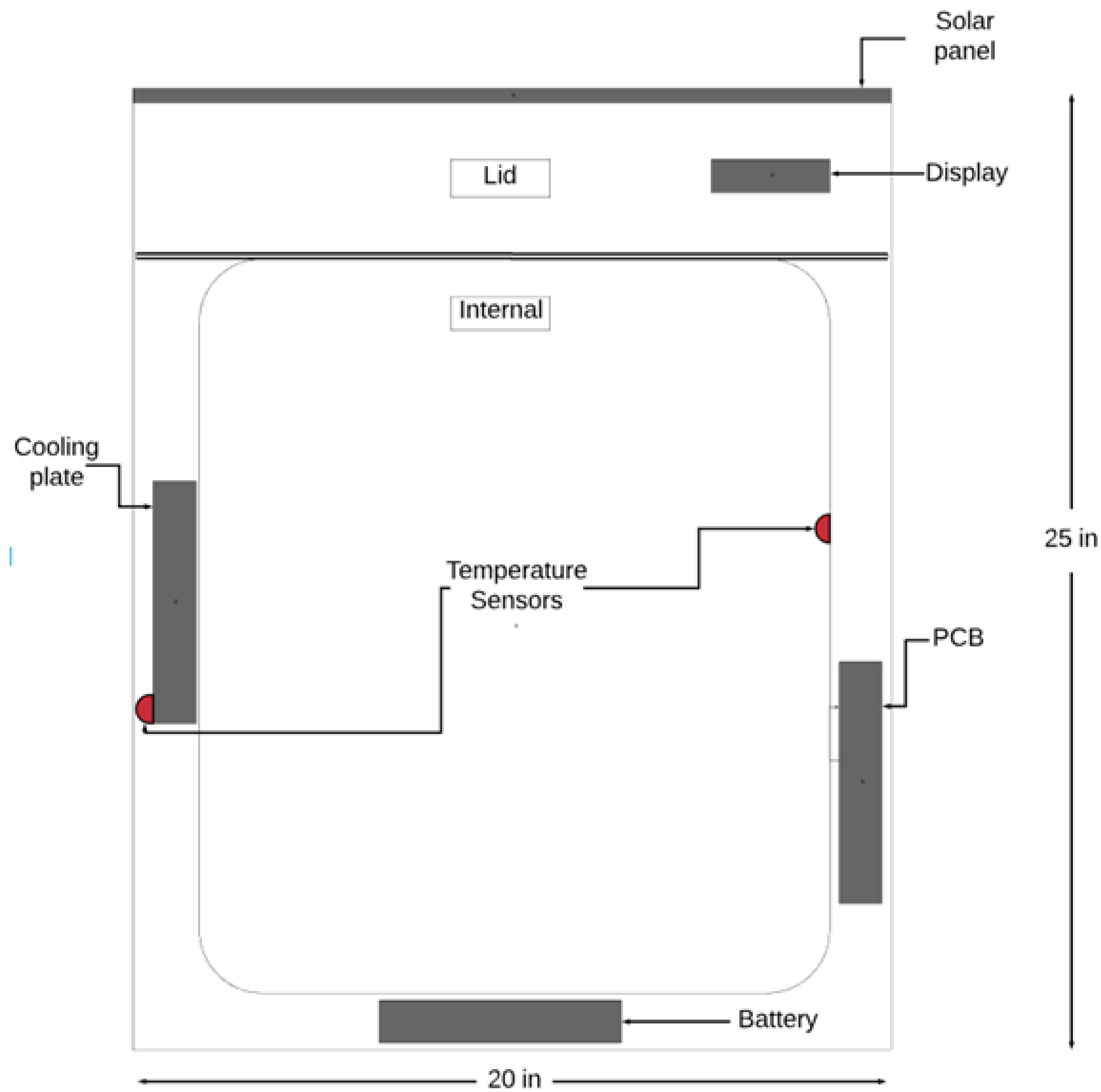

Figure 2: Physical Design Diagram

The dimensions of the cooler will be 25” x 20” x 25”. The inner casing must be waterproof so that no water leaks out of the case onto the battery or solar panel. The battery and PCB will be on either side of the walls of the cooler and the solar panel will be placed on the lid of the cooler for maximum sunlight. The solar panel will be 23” x 14”.

2.3 Functional Overview and Block Requirements

2.3.1: Power Unit

2.3.1.1 Solar Panel

Solar panel will charge the system by converting light energy to electrical energy. We have selected a monocrystalline silicon panel module for a lightweight and robust component [1].

Since one of our requirements is to charge the 120Wh battery in under 7h, we have selected a 25W solar panel such that this is feasible even under mildly cloudy conditions. The calculation is as follows:

$$120Wh/25W = 4.8h \tag{1}$$

Requirements	Verification
1) The panel can provide up to 25W, at 18V and 1.4A under maximum power delivery conditions. 2) The solar panel charge the battery 120Wh (10Ah) fully in one day, or in other words, under 7 hours of sunlight.	1) Obtain Solar panel I-V curve and find maximum power point. 2) Verify maximum power point will fully charge battery in under 7 hours. The solar panel should provide power in the range 17.2 - 25 W.

2.3.1.2 Charge Controller

The charge controller is responsible for controlling the flow of charge into the battery from the solar panel. This will component will be responsible for regulating input voltage into the battery and prevent overcharging, discharging and damage of the battery. We choose to use *bq24650* charge IC, see Appendix B for pin description of the charge controller. It can take in 5V to 28V input solar panel which will be adequate for 18V solar panel. The IC can monitor the battery and stop charging when the battery is full. Another feature of *bq24650* is that there is maximum power point tracking capability so that battery can be efficiently charged [9].

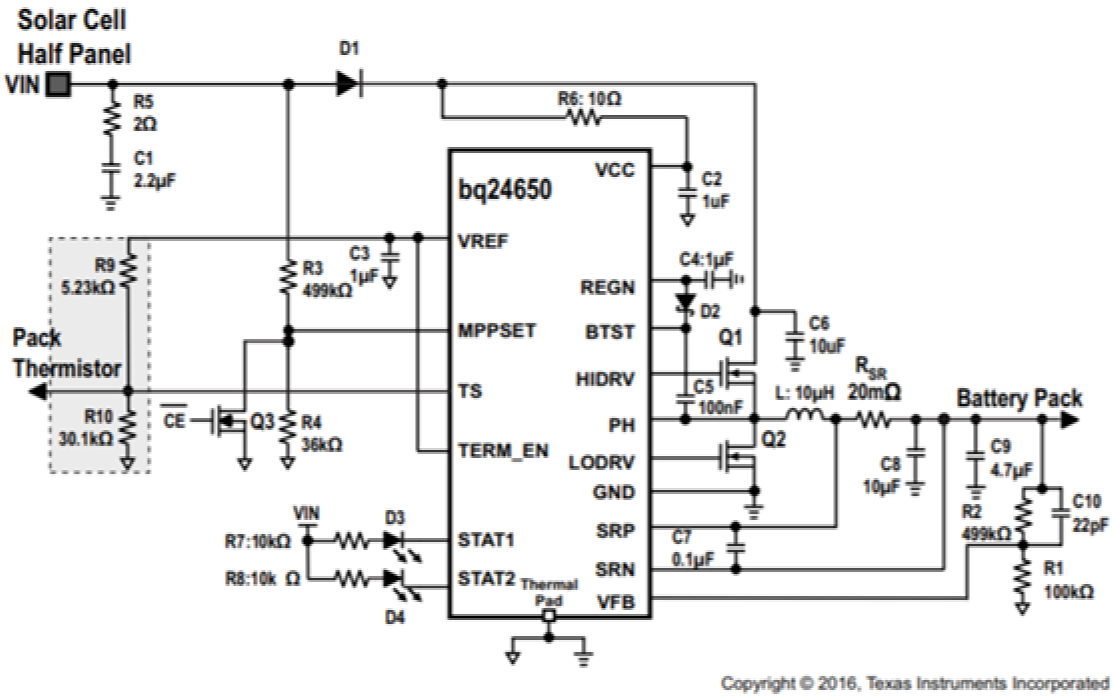

Figure 3: Schematic with Input from Solar Panel and Output to Battery [9]

The VIN in Figure 3 will be connect to the output of the solar panel and the arrow located at the bottom right of the figure will be connect to the Li-ion battery. A 3A fuse will also be connected between the solar panel and the input of the charge controller to prevent possibility of short circuit.

The 3 MOSFETs in Figure 3 (Q1, Q2 and Q3), are dual N-channel MOSFETs. Q1 and Q2 will be using Si7288 with drain-source voltage rating of 40V [13]. Q3 will be using 2N7002 which has drain-source voltage rating of 60V [14].

Requirements	Verification
1) Must provide battery with 12 - 14V, when battery is not fully charged. 2) Stop charging battery when battery is fully charged. 3) Disconnect power from rest of the circuit if 3A is exceeded.	1) With a DC power supply providing 18V and 1.2 A. Measure output voltage using voltmeter. Make sure it is between 12 - 14V. 2) Measure power output (to battery) when a fully charged battery is connected. Make sure that there is no output from the charge controller. Also check the STAT1 and STAT2 to ensure they are HI and LOW respectively which shows charge is complete. 3) Measure current using ammeter with an increasing current (up to 5A) from a DC power supply.

2.3.1.3 Li-ion Battery

The Li-ion battery will supply the power to the system. It will store the excess power from the solar panel when sunlight is available. We use a 12V Lithium battery with capacity of 10 Ah [4]. If the cooling plate operate at current 3A, then with a fully charged battery it can run for:

$$\frac{10\ Ah}{3A} = 3.33\ Hrs \tag{2}$$

Requirements	Verification
1) Fully charged battery should power the system for at least 2 hours with discharge voltage of 9.0 - 11.0V.	1) Measure the output voltage of the battery with a multimeter while the system is running. The multimeter should read in range 9.0 - 11.0V. 2) Attach a 2A load battery tester and ensure the load is supplied for at least 2 hours via a voltmeter/ammeter.

2.3.1.4 Voltage Regulator

The voltage regulator will regulate voltage from battery to the control, sensor, and cooling units. The role of this component is to supply a constant operating voltage of each component. The voltage regulator will output a constant voltage of 5V with the input from the battery. We will use *LM1084* 5V voltage regulator, it will output at maximum current of 5A [10]. This will provide enough power to all other units. Figure 4 shows the implementation of the unit. The V_{in} will be connected to the output of the Li-ion battery and V_{out} will provide the power to microcontroller, temperature sensors, thermoelectric cooling plate and display.

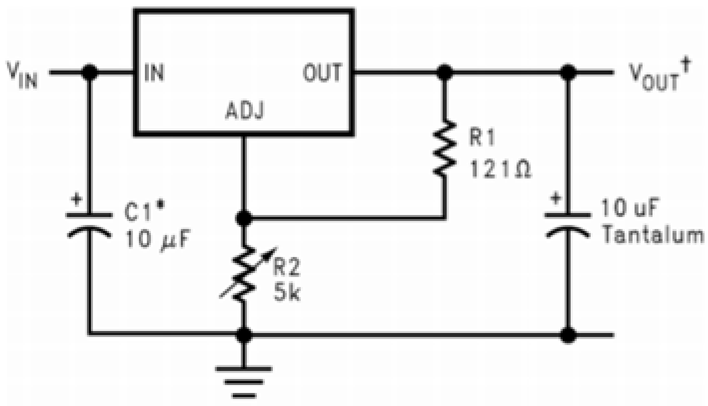

Figure 4: schematic diagram of Voltage Regulator

The resistors R1 and R2 in Figure 4 should be chosen so that is match with the following:

$$V_{out} = 1.25 * (1 + \frac{R_2}{R_1}) \quad (3)$$

Thus, for V_{out} to be 5V we will need $\frac{R_2}{R_1}$ = 4.

Requirements	Verification
1) Output voltage should be in the range 4.8- 5.2V	1) Provide the voltage regulator with 11V from DC power supply. Measure output voltages using voltmeter. Verify the voltage is in the range 4.8- 5.2V.

2.3.2 Control Unit

2.3.2.1 Microcontroller

We will use ATMEGA328-PU [11] the microcontroller will serve to provide control voltages to the surrounding units. It will receive 1-bit input data each from the two temperature sensors and display the corresponding temperature information by sending 13 bit data to the 7 segment display. It is also capable of sending one control signal to the cooling plate to switch it on or off.

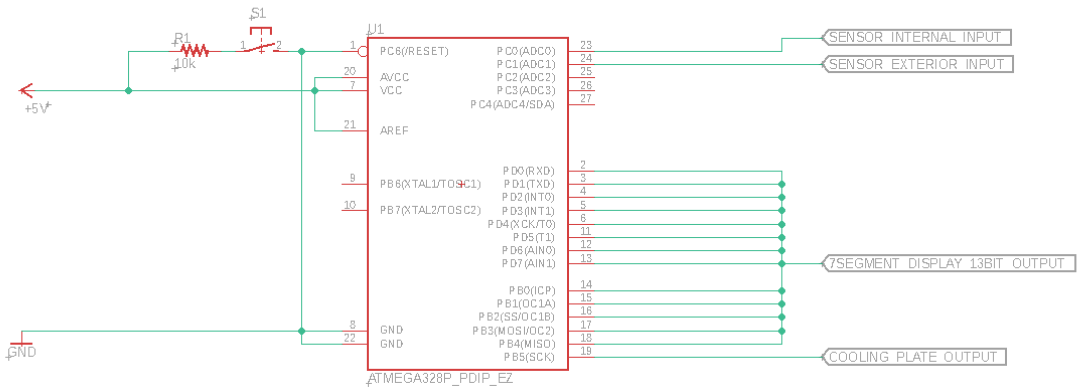

Figure 5: Schematic for microcontroller

The operation of turning cooling plate will follow the flow chart in Figure 6. Notice that when temperature is in between 3 - 5 Celsius, the plate will be on and off depend on its last state. For example, if the cooling plate is in ON state, it should continue be ON state until it reaches 3 Celsius. If the cooling plate is in OFF state, it should continue be OFF state until it reaches 5 Celsius. This range is used so that the cooling plate does not switch on and off rapidly at the boundary.

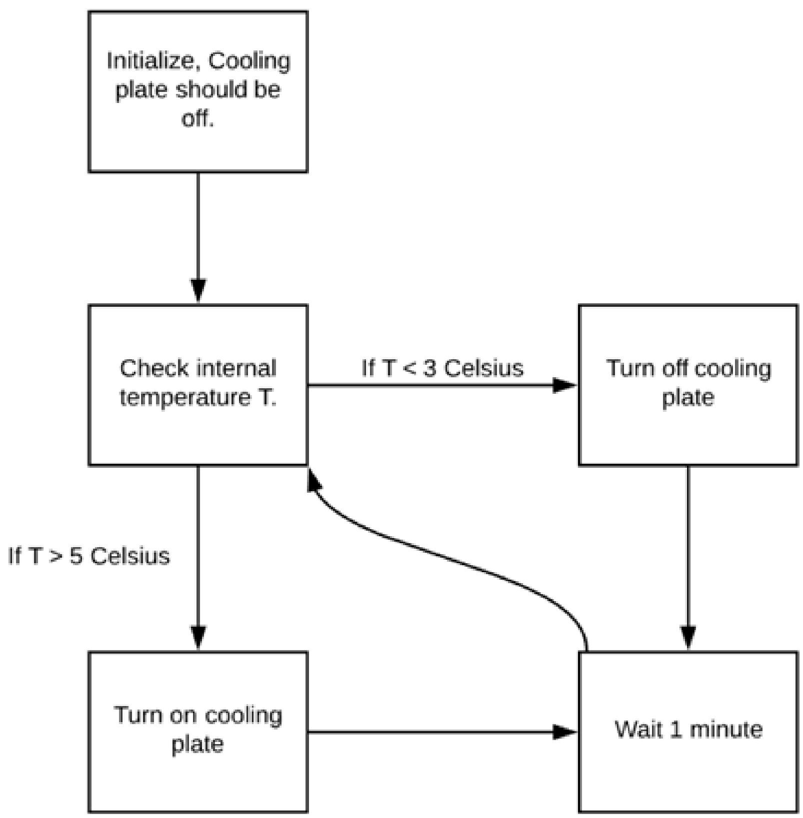

Figure 6: Operation of the Cooling plate

Requirements	Verification
1) Must be able to sense the voltage from temperature sensor with at least 5mV increment. 2) Microcontroller can output correct signal to the display to display correct value.	1) Send the voltage to the microcontroller with function generator from 2.00V to 3.00V in 5mV increment. Check the readout on the microcontroller which will be setup to be display on the 7-segment display. Make sure it can detect difference in 5mV. 2) Program the microcontroller to display 0 - 9 on each of the four-character display. Verify that all segment is working correctly, and the display does display the correct value.

2.3.2.2 7-Segment Display

The 7-Segment Display [6] will be the monitor for our solar cooler. This will display the internal temperature of the cooler in Fahrenheit. The temperature data will be provided by the temperature sensor located inside of the cooler which will be send to microcontroller. The microcontroller will control the display to display the correct value. We will be using the *LTC-4727JR*, it is a four-character LED display. As shown in Figure 7, Digit 1 will display the sign, Digit 2 and Digit 3 will display the tenth and ones place respectively, Digit 4 will display F to show the temperature is in Fahrenheit.

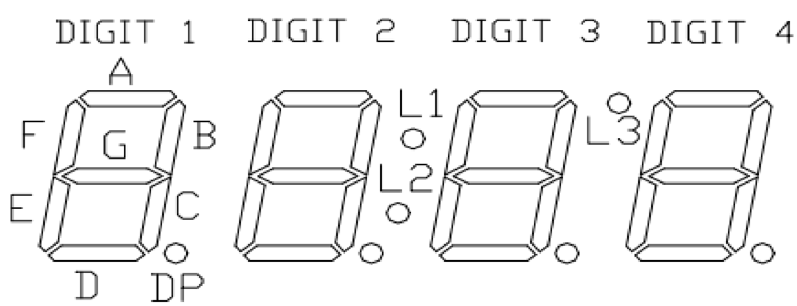

Figure 7: Physical layout of the digits.

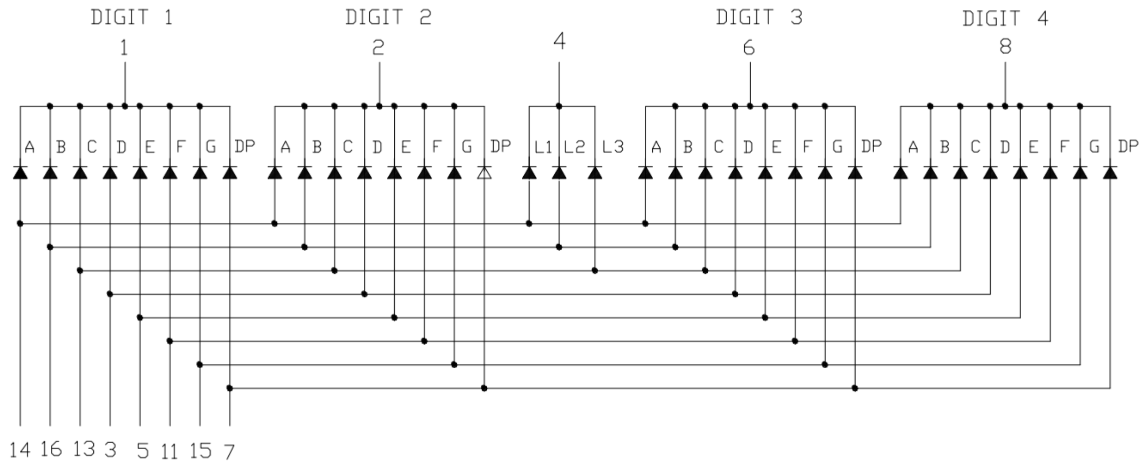

Figure 8: Internal layout of the display

According to Figure 8, all the segments of a particular digit control by the same pins with pins 1, 2,6,8 control which digit to show (See Appendix C for pin description). Thus, microcontroller will need to cycle through each digit individually oppose to showing all four digits at the same time.

Requirements	Verification
1) The 7-segment will operate at 4.8 - 5.1V. 2) The display can successfully reflect the internal temperature in F.	1) Using a DC power supply, with one end at cathode to GND and 5V at anthode of a segment. Measure the voltage with a multimeter. Verify the voltage is in 4.8-5.1V. 2) Put the module inside of a refrigerator, see if the display temperature matches the display temperature of the refrigerator.

2.3.3 Sensor Unit

2.3.3.1Temperature Sensor

There will be two sensors, one will detect the internal temperature of the cooler, another will detect the temperature on the hot side of the cooling plate to prevent overheating. The sensors will provide feedback to the microcontroller which will control the cooling plate. We will be using LM335AH [12] as our temperature sensor. The sensor will provide 1 Celsius accuracy with wide operating temperature range from -40 to 100 Celsius [12]. The output of the sensor is linear, which makes reading the value easy without too much of calibration. For the sensor placed inside of the cooler, it will be wrapped with heat shrinkable tubing for waterproof.

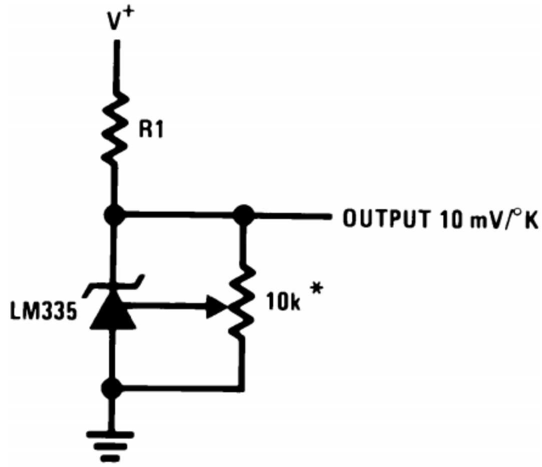

Figure 9: Schematic diagram for temperature sensor [12]

We note that in the 3-pin configuration shown in Figure 9, we will need a Vcc and GND voltages which is provided by the voltage regulator, and output signal to the microcontroller. We expect temperatures between -5 to 30°C with an accuracy to +/- 1°C. With these requirements, we expect the output voltage of Figure 8 to be:

$$(273.15 - 5) * 10mV < V_{out} < (273.15 + 30) * 10mV \quad (4)$$

$$2.68V < V_{out} < 3.03V \quad (5)$$

The microcontroller must be able to identify a $5mV$ difference in V_{out} to meet these requirements.

With V^+ = 5V which is the voltage that voltage regulator provides, R1 should be chosen so that the current is 1 mA. So R1 will be 5000 Ω.

Requirements	Verification
1) The sensor should detect temperature with accuracy of at least 1°C in the range -5 to 30°C.	1) A thermometer will be place inside of the cooler and the outer temperature of cooling plate can be monitor with a heat gun. The measurement will be comparing to the value output by the temperature sensors. The difference should be below 1 Celsius.

2.3.4 Cooling Unit

2.3.4.1Thermoelectric Cooling Plate

The cooling plate will cool and maintain the internal temperature of the cooler which will be control by the microcontroller. The power will be supply by the voltage regulator. It will achieve this by transferring the heat from the cold side of the plate(internal) to hot side of the plate(external). Heatsink will be attached to the hot side of the plate so that heat can escape properly to outside of the cooler. Temperature sensor will also be placed near hot side of the plate to monitor for risk of overheating. Cooling plate *387001842* will be used for the application. It is able to handle maximum of 4.56 V and 9.0 A [5].

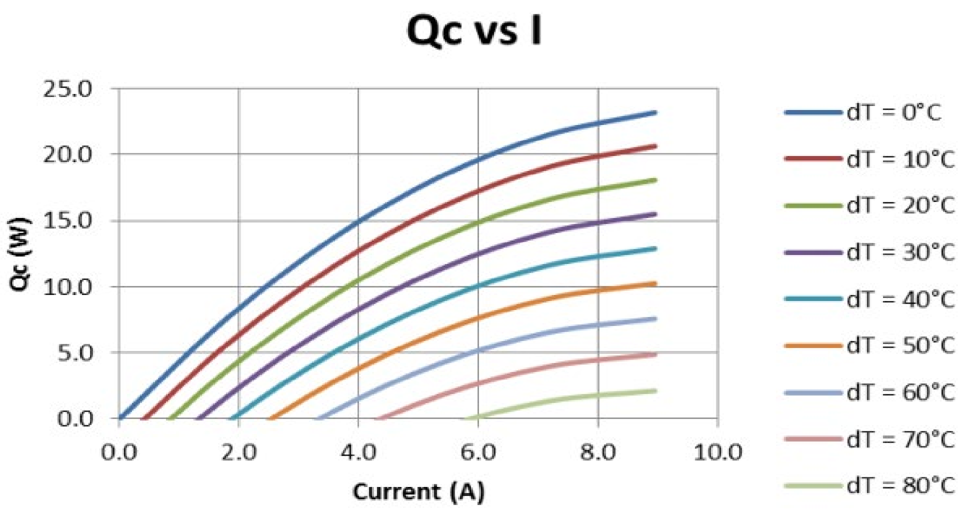

Figure 10: Heat extract vs input current at various temperature difference [5]

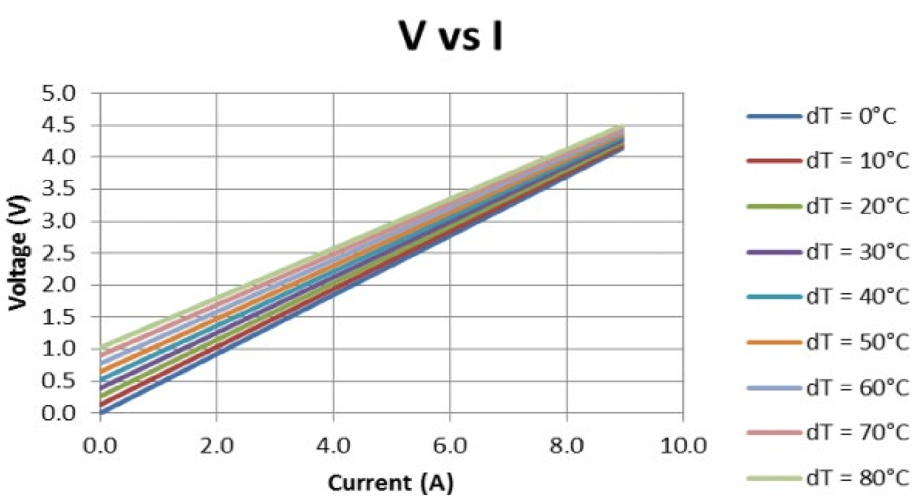

Figure 11: I-V curve of Thermoelectric cooling plate [5]

From Figure 10, we can see that at input current of 3.5A, Qc is in the range roughly 8.5 - 14W for dT = 0 to 20 Celsius. From Figure 11, at current of 3.5A, operating voltage is in the range 1.6 - 2 V for dT = 0 to 20 Celsius.

Here we will calculate length of time needed to cool 12 pack coke which is around 4.5 kg, in room temperature to our desired temperature in a reasonable amount of time. We will use two cooling pads, and assume the room temperature is 20 degrees Celsius, outside temperature is 30 degrees Celsius, thus we have to cool the 12-pack coke from 20 degrees to 10 degrees. To make the calculation more fault tolerant, we assume the worst case of Qc = 8.5W per cooling pad and assume the internal dimension of the cooler is 21'' x 16'' x 21'', note that this is an overestimation of the actual cooler. We assume the coke has the heat capacity of water which is 4186 joule/kg °C. We want to know the time to cool the items, which is given by the equation

$$t = Q_{drink}/(Q_c - W_{ambient}) \quad (6)$$

$W_{ambient}$ is 8 Watt calculated from equation (16), which is the heat flow from outside to inside, and Q_{drink} can be calculated with:

$$Q_c = weight * heat\ capacity * \Delta T \quad (7)$$

$$= 4.5kg * 4186\ joules / kg\ C*10 \quad (8)$$

$$= 188370\ Joules \quad (9)$$

Now plug in the numbers back to equation 6, for Q_c of 17 Watt, which is ability of removing heat of the two cooling pads, the time to cool is

T = 188380 / (17-8)/3600 (10)

T = 5.8 hours (11)

This time is reasonable since our primary goal of the cooler is to maintain the temperature, and the drinks that the user put in is very likely to be cooled already.

Requirements	Verification
1) Should cool the internal to 20 Celsius below the ambient temperature with only air inside within 20 minutes. 2) The hot side of the plate should not exceed 80 Celsius [5].	1) Supply power with 3.5A to 2 plates connecting in series and monitor temperature changes via temperature sensor (or thermometer) inside of the cooler. Make sure internal temperature of the cooler is 20 below the ambient temperature after 20 minutes of operating. 2) While testing requirement 1, use a heat gun to check the temperature of the hot side of the cooling plate and verify it is under 80 Celsius during the operation.

2.4 Risk Analysis

Since the device will be portable and designed to be taken to picnics, we must consider the potential risks of all the component. Firstly, we must consider that the overall rig may be dropped. With that being said, this can cause leakages in the battery and cause damage to the circuitry. Secondly, we must consider potential leaks from the packages or food stored within the cooling compartment; the liquids, if exposed to any of the electrical circuits can cause the subsystems to behave differently that intended, leading to undesired results or total loss of functionality; also, this can cause shocks. Thirdly, we need to monitor the temperature on the cooling plate, there is possibility that overheating could occur during the operation as heat might not escape the system fast enough. The solutions to these risks will be addressed in the following safety section.

2.5 Tolerance Analysis

We are building a solar cooler for people who can't always buy a bag of ice or thinks the traditional cooler doesn't last long or is too heavy. The cooler uses thermoelectric cooling, it has a thermoelectric cooling unit that can remove 8.5 W of heat is implanted into a regular insulting box. The box will insulate 100% of water and some heat base on the k value, which is the thermal conductivity. The cooling unit can remove 8.5W of heat and is being powered by the battery, and the battery can be charged with an outlet or with solar power.

The critical component in our design is the cooling component, which involves how to remove the heat and how to prevent the heat from flowing inside. We want the time to cool the items inside as low as possible, so we listed an equation that describes the heat flow in the system.

$$W_{ambient} * t = Q_c t - Q_{drink} \quad (12)$$

In the equation, $W_{ambient}$ is the rate of heat transfer from the environment into the box, t which is the time it takes for the drinks to cool to the cooler temperature, and $Q_c$is how much heat the thermoelectric component can remove, in watts, and $Q_{drink}$is the heat that the drink will release into the environment and thus need to be removed.

Solve for t:

$$W_{ambient} * t = Q_c t - Q_{drink} \quad (13)$$

$$Q_{drink} = Q_c t - W_{ambient} t \quad (14)$$

$$Q_{drink} = t(Q_c - W_{ambient}) \quad (15)$$

$$t = Q_{drink}/(Q_c - W_{ambient}) \quad (16)$$

The denominator of the left side shows that, in order for the cooler to stay cool, the heat removed should at least equal to the heat moves in.

The most critical aspect of our project's performance is that it at least be able to cool the drinks. As shown in equation (5), the cooler will stop cooling if the heat transfer from outside is higher than 8.5W which is the speed at which the cooling component can remove heat. For the tolerance analysis, we will investigate in the worst case (1) the heat transferred from outside into the cooler.

Our cooler has three layers, the inner layer should be water resistant and the outer layer is responsible for possible collision, the insulation is the layer in the middle that is responsible for keeping the temperature of the cooler, but heat will still transfer, the rate at which the heat transfer, the $W_{ambient}$, can be expressed with "Fourier's Law"

$$W_{ambient} = k * A * \nabla T/d \quad (17)$$

Where k is the thermal conductivity value of the insulation material. The insulation material we chose is the Polyurethane foam, that has heat conductivity of 0.025W/mK. The **∇**T is the difference in temperature between outside of the cooler and inside of the cooler. d is the thickness of our material in meters, which we have chosen to be four inches. material and the thermal conductivity of our material. The thermoelectric cooler can remove up to 8.5 Watts of heat, and our inner layer of the cooler has dimension of 21'' x 16'' x 21", thus the area is

$$(0.5374m * 0.4064m + 0.5374m * 0.5374m + 0.4064m * 0.5374m) * 2 = 1.45m^2 \quad (18)$$

All the variables above can be controlled, except the thermal conductivity, which is dependent on the temperature, the density and the moisture content of the material. For polyurethane, it could range from 0.02 W/mK to 0.028W/mk [8]. We will calculate the heat transferred in the worst case, when the foam has thermal conductivity of 0.028W/mk. The cooler temperature must be 20 Celsius lower than the ambient temperature, thus **∇**T is 20. Plug in the numbers to equation:

$$W_{ambient} = 0.028W m^{-1} K^{-1} * 1.45 m^2 * 20C/0.1016 \quad (19)$$

$$W_{ambient} = 7.99 Watt \quad (20)$$

The heat introduced to the cooler is less than the amount of heat the cooler can remove (8.5 W).

3. Cost & Schedule

3.1 Labor and Part Cost

The national average salary for a BS ECE graduate is $96,518. The graduate tends to work 40 hours per week, and there are 52 weeks in a year. The ECE graduate earns about $46.4 per hour. We have three people and are planning to work on the project 12 hours for 16 weeks. The total is 16 weeks * 12 hours * 3 person * 2.5 * $46.4= $53452.8.

Table 1: Cost for Each Parts

Description	Part #	Manufacturer	Price per Unit	Price in Bulk	Quantity
25W Solar panel	NPA25-12	Newpowa	$39.97	$39.97	1
Thermoelectric Cooling Plate	387001842	Laird Technology	$22.70	$20.02	1
Microcontroller	ATMEGA328-PU	Microchip Technology	$1.96	$1.63	1
Lithium 12V Battery	CR12V10AH	Dakota Lithium	$99	$99	1
Temperature Sensor	LM335AH	Texas Instrument	$1.13	$1.13	2
Battery Charger Controller	bq24650	Texas Instrument	$5.52	$4.07	1
3A Fuse	AGC-3	AllFuses	$1.03	$1.03	1
5A Fuse	AGC-5	AllFuses	$1.62	$1.62	1
5V Voltage Regulator	LM1084	Texas Instruments	$2.60	$1.14	1
7-segment display	LTC-4727JR	Lite-On Inc.	$3.96	$1.65	1
PCB	N/A	PCBway	$0.00	$0.00	1
Cooler container	1031510	Huskee	$12.97	$12.97	1
Heatsink	655-53AB	Wakefield-Vette	$2.03	$1.39	1
		Total:	**$195.62**	$186.75	
		Grand Total:	**$54646.39**		

3.2 Schedule

Table 2: Schedule for each member

Week	Hanfei	Karim	Kunjie	Group
2/25	Buy Parts and work on next week job if parts arrive early	Buy Parts and work on next week job if parts arrive early	Buy Parts and work on next week job if parts arrive early	Buy Parts
3/4	Burn Bootloader to microcontroller, test microcontroller	Parts Testing--Power	Parts Testing--Sensor, Display, Cooling	Soldering Assignment
3/11	Program microcontroller	Make sure battery and be charged with solar panel	Design PCB.	Order PCB
3/18	Meet up with Kunjie to integrate microcontroller into other components	Build the Cooler, integrate power component to the cooler	Meet up with Hanfei to integrate Sensor, Display, Cooling	Spring Break
3/25	Integrate control component to the cooler	Integrate power component to the cooler	Integrate control component to the cooler	Final Round PCB order
4/1	Debug	Debug	Debug	Debug
4/8	Verify the Cooler fits requirement	Verify the Cooler fits requirement	Verify the Cooler fits requirement	Prepare for Mocking Demo
4/15	Final Report	Final Report	Final Report	Prepare for Demo and Mock Presentation
4/22	Debug Control Component	Debug Power Component	Debug Cont.	Prepare for Presentation
4/29	Prepare for Presentation	Prepare for Presentation	Prepare for Presentation	Prepare for Presentation

4. Ethics & Safety

There are two main safety concerns we must worry about. First, due to the nature of the device, the system must be robust. The circuitry and items inside the cooler must be contained separately. The system must be waterproof to avoid shocks and the battery, in case of any leakages, has been chosen as lithium ion and not SLA (sealed lead acid) due to the toxicity of SLA. Second, we must make sure the cooler door and parts are robust so that not sharp edges can be formed by wear and tear of cooler use. Third, the temperature sensor placed on the cooling plate will make sure there is no overheating during operation.

We have to make sure we don’t violate IEEE Code of Ethics [3] and ACM Code of Ethics [2] by avoiding injuring others. Through the use of our cooler, there is a chance that the cooler will malfunction, we will try to minimize the chance and mitigate the harm as much as possible. When release the product, we will follow the IEEE Code of Ethics [3] code number one by disclose promptly factors that might endanger the public or the environment.

Our project will very likely to accept help from many people, including TA, professor, friends, and people who have done similar projects in the past, we will follow IEEE Code of Ethics [3], seek, and accept criticism of technical work, improve our work base on the feedback and credit others properly.

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Appendix A. (Microcontroller)

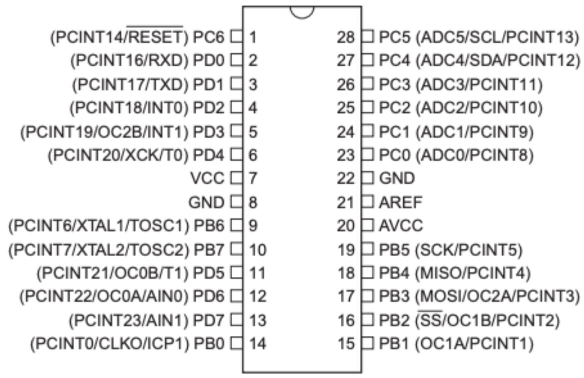

Figure A.1: Pin layout

Pins	Pin Description
VCC	Digital Supply Voltage
GND	Ground
PB[7:0]	Bi-directional I/O port, tri-stated if reset condition active
PC[5:0]	Bi-directional I/O port, tri-stated if reset condition active
PC[6]/RESET	If RSTDISBL Fuse programmed: I/O pin If RSTDISBL Fuse not programmed: Reset input
PD[7:0]	Bi-directional I/O port, tri-stated if reset condition active
AVCC	Supply voltage for A/D Converter, PC [3:0] and ADC [7:6]. Needs to be externally connected to VCC through a low pass filter.
AREF	Analog reference pin for A/D conversion
ADC[7:6]	Analog inputs for A/D converter

Table A.2: Pin description

Appendix B. (Battery Charge Controller)

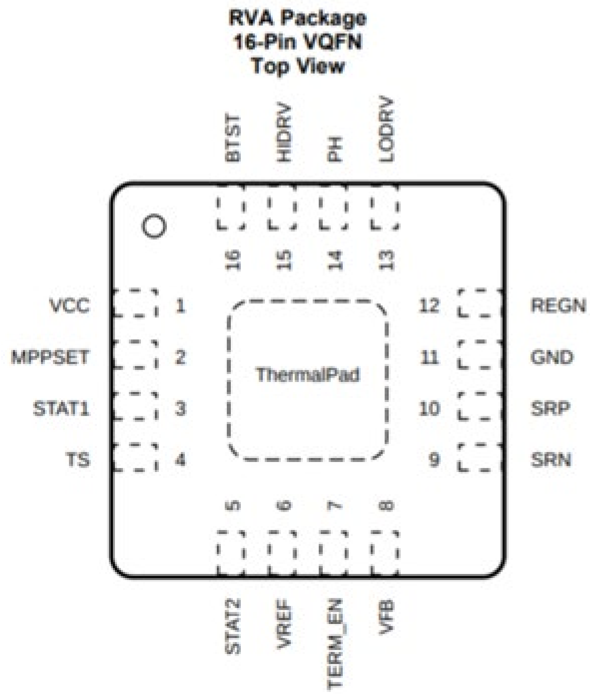

Figure B.1: Pin layout

Pins	Pin description
VCC	Positive power supply. For our application, 18V solar panel will be the power supply.
MPPSET	Input voltage set point. Stop charging at below 75mV.
STAT1	Charge status output. LOW indicates charge in progress. HI otherwise.
TS	Temperature voltage input.
STAT2	Charge status output. LOW indicates charge complete. HI otherwise.
VREF	3.3V reference voltage output.
TERM_EN	Charge termination enable.
VFB	Charge voltage analog feedback adjustment.
SRN	Charge current sense resistor.
SRP	Charge current sense resistor.
GND	Power ground.
REGN	PWM low-side driver positive 6-V supply output.
LODRV	PWM low-side driver output.
PH	Switching node, charge current output inductor connection.
HIDRV	PWM high-side driver output.
BTST	PWM high-side driver positive supply.

Table B.2: Pin description

Appendix C (7-segment Display)

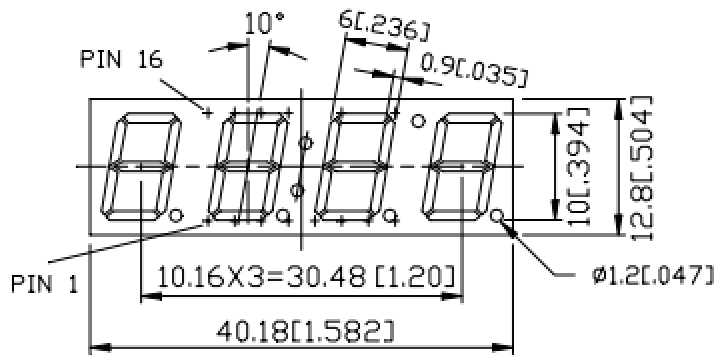

Table C.1: Pin layout

Pin	Pin description
1	Cathode Digit 1
2	Cathode Digit 2
3	Anode D
4	Cathode L1,L2,L3
5	Anode E
6	Cathode Digit 3
7	Anode DP
8	Cathode Digit 4
9	No connection
10	No connection
11	Anode F
12	No connection
13	Anode C, L3
14	Anode A, L1
15	Anode G
16	Anode B, L2

Table C.2: Pin description