From Schematic to Product: Designing a low cost temperature sensor module

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Abstract

This paper presents the results of a student-led project that was done as a final project in an undergraduate course in Electric Circuits. The project was a team project where the students were asked to form interdisciplinary teams of two to four students. The project consisted of four circuit designs and each team was asked to choose one of the circuits for their final project. Our chosen circuit was the design of a temperature sensor using a 741 operational amplifier. Initially, each group was required to thoroughly research a sample schematic, and create an improved version, as well as carry out detailed tests of their design. The end goal was to create an application, proposal and presentation for their design. The proposals were required to be very detailed, including all technical details, testing plans and results, bill of materials and cost analysis done using prices from online component distributors. Once the proposals were completed, the teams were required to present their proposal to the instructor, with the winner for each circuit design category moving on to a secondary round. While the presentations for the first round had to be completed by the teams themselves, for the second round an instructor helped the team by providing feedback and recommendations on how to improve any troublesome parts of the presentation, product design and testing procedure. This paper will describe the project, then it will show the methods and design of the winning team, and discuss the process taken by the team to achieve the end result.

Introduction

This paper describes the work of the winning team of a student-led project that was done as a final project in an undergraduate course in Electric Circuits course at Ohio Northern University. The idea of having a final project in the Electric Circuit class was first introduced[1] in 2012 and then a modified version of the project[2] was presented in 2013. In the previous two years, all students from all sections were given only one circuit to design, however in this year's project the students are given multiple circuits to choose from, and depending on their project, the students are introduced to some of the fundamental electronic devices such as diodes and transistors, and some of the widely used sensors such as piezoelectric sensors.

The Electric Circuits course at Ohio Northern University is required for students in Electrical, Computer, and Mechanical Engineering, and for Engineering Education students. It is a four credit hour semester course consists of three 50 minutes lectures and a 2 hour associated laboratory each week, and is considered one of the core courses in the Electrical Engineering curriculum.

The project goals are to help the students to work in multi-disciplinary teams, perform an independent research study, analyze the functionality of a given circuit and propose alternative designs, simulate the circuit using PSPICE, construct circuit on breadboard, test the functionality of the circuit, and to build a PCB prototype. In addition to these goals, the students were introduced to the entrepreneurial mindset and its relation to design and fabrication by performing market analysis for the manufacturing of the circuit. The expected outcomes of the project agree with the entrepreneurial skills specified by the Kern family foundation that are believed to contribute to a breakthrough innovation[3,4]. The outcomes are: effective collaboration and communication, persisting and learning from failure, solving problems, and project management.

The students are expected to organize themselves into groups of two to four, comprised of students from at least two different disciplines. The group task is to study the functionality of the circuit and to come up with an alternative circuit for real life applications. Each group is given the chance to choose one circuit out of four circuits, then the group is required to research all the parts of their chosen circuit. Once the group completely understood the process by which the design worked, as well as the functionality of the design, they needed to create their own alternative design. For our chosen circuit of Car's Overheating Temperature Alarm, the alternative design needed to be able to receive power from a vehicle, use a Negative Temperature Coefficient thermistor, and output a signal using green and red status light emitting diodes. To be considered an improvement over the provided design, the goal of this alternative design was to improve the original design, by reducing the cost required for construction.

Project Description Given to Students

The project objective is to design an overheating temperature alarm to protect the vehicle's engine from overheating, The Car's Overheating Temperature Alarm circuit is shown in Figure 1.

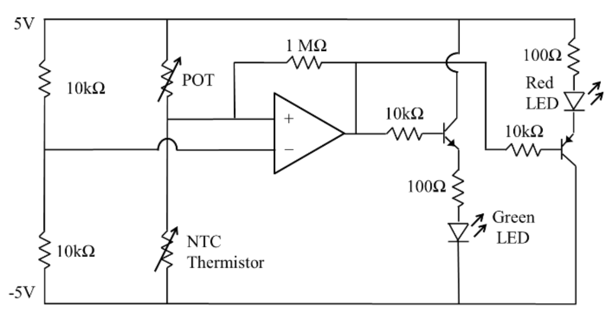

Figure 1: Car's Overheating Temperature Alarm circuit

The alarm system utilizes a thermistor, which is a variable resistor whose resistance value varies significantly with temperature. If the temperature is too high, the red LED should illuminate; if the temperature is sufficiently low, the green LED should illuminate. It is the company's job first to determine the appropriate temperature threshold for the alarm and then to select the potentiometer involved in the voltage division with the thermistor appropriately to make that threshold work for your circuit. The threshold should be part of the design and consistent with the desired application.

This design uses a Negative Temperature Coefficient (NTC) thermistor, whose resistance decreases with increasing temperature. The specific model you are to use is the RL1005-5744-103-D1 (the data sheet is provided separately). The temperature dependence of an NTC thermistor is given by the equation:

$$\beta = \frac{ln(R/R_0)}{1/T - 1/T_0}$$

where T_0 is the reference temperature in Kelvin [K], R_0 is the resistance of the thermistor at the reference temperature in ohms [Ω], T is the temperature under consideration (in Kelvin), R is the resistance of the thermistor at temperature T, and β is a constant called the B-constant (measured in Kelvin), which is used for a given temperature range to approximate the temperature-resistance dependence. For the RL1005-5744-103-D1 model, T_0 = 298.15[K] (equal to 25˚C), R_0 = 10[kΩ], and β = 4073[K] for the range of 25˚ to 85˚C. The error tolerance for this model is ±10% (in resistance at a given temperature). The power dissipation constant (δ in the data sheet) at 25˚C is 2.5mW/˚C. This parameter specifies the power dissipation per degree Celsius. Keep this and other power considerations in mind for your design (especially, how will the circuit be powered along with battery life). Be careful operating the NTC thermistor above the mA range, in which case self-heating can be a problem, and significantly complicates the analysis.

Deliverables:

The first deliverable required each company (team) to conduct research and understand the functionality of all the electronic components of their selected circuit; some of these components such as diodes, transistors, thermistors and sensors were not introduced in the Electric Circuit class, so the student had to read about those components and understand how they function. Then they had to submit a detailed explanation of the involved components and describe the overall functionality of the selected circuit. The second deliverable required the teams to provide an alternative design solution based on their understanding of the functionality of the circuit. The alternative design must meet the customer's needs along with an explanation of which design is better. The company then must compile a product proposal, which should include at minimal a bill of materials, cost analysis (include labor in a break-even analysis based on monthly production), circuit design and simulation, testing plan, layout of PCB and packaging schematic, and delivery time. Additionally, a prototype of the design should be built and tested according to the test plan. The students were asked to build their circuit using a breadboard. They were given the opportunity to fabricate PCBs for their working prototype. Below is a list of the specific deliverables for the project:

1. 2-3 pages that cover the functionality of each component in the selected circuit along with the explanation of components integration and interaction to show the functionality of the whole circuit. In addition, teams have to provide an alternative design solution that results with the same functionality per customer specifications.
2. 7-12 pages written proposal with PSpice simulation.

3. Circuit prototype with specification sheet (attached to proposal).
4. 5-minute pitch for the team to sell their product using a PowerPoint poster.

Circuit Design and Simulation

Our circuit went through two revisions before it was constructed. The original design, shown in Figure 1, was the one provided to us by our instructor. It consisted of one operational amplifier, 8 resistors, two transistors, two light emitting diodes and one thermistor. Our design which we eventually built, featured a slightly modified setup from the original design to allow for a single power source. This design used one operational amplifier, 8 resistors, two transistors, two light emitting diodes, one thermistor, two capacitors, and a linear regulator. The design is shown in Figure 2.

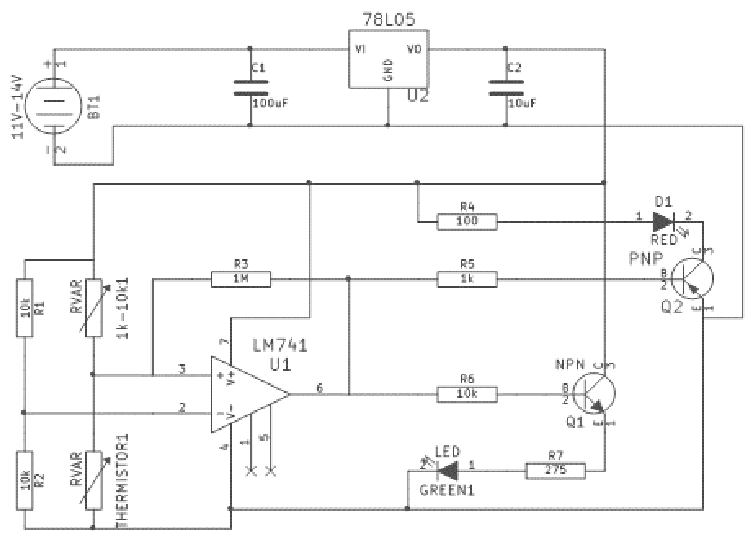

Figure 2: Circuit Diagram of the proposed and constructed circuit

The two 10kΩ resistors create a constant voltage reference for the V- input of the operational amplifier, while the variable resistor and the thermistor create a varying voltage for the V+ input of the op amp. As the thermistor heats up from 25°C to 100°C, its resistance decreases from 10kΩ to 1kΩ.

The operational amplifier works in two states. While the resistance of the thermistor is greater than the potentiometer, the operational amplifier outputs 5 volts. When the resistance of the thermistor drops below that of the potentiometer, the operational amplifier switches from 5 volts to 0 volts almost instantaneously. This is what allows the device to either illuminate the red or the green led, without the concern of both LEDs illuminating at once.

The output section of the design are the two transistors and their LEDs. The NPN transistor used on the green LED causes the green led to illuminate when the op amp output is at 5 volts, by allowing current to flow through it. When the voltage drops to 0 volts, the NPN transistor blocks the current flow to the picoamp range, turning off the green LED. The PNP transistor works in the opposite way, blocking current flow when the op amp output is 5 volts, and allowing the red LED to illuminate when the op amp output is at 0 volts.

The power section of the circuit is a basic linear regulator design. Because the circuit is designed to be used in a vehicle, the system should be able to be powered off of an automobile's electrical system, which runs between 11 and 18 volts. For this, a 7095 linear regulator is used. It is able to convert any voltage between 7.5 and 20 volts down to a consistent 5 volts for the operational amplifier. Two electrolytic capacitors are used to filter out any interference from the linear regulator, a 100µF capacitor on the input side, and a 10µF capacitor on the output side.

Prototype Construction and Testing

The prototype construction was a somewhat lengthy process that we went through to make sure that it would be able to operate properly. The circuit was first designed and simulated in PSPICE. This allowed us to test out ways to improve the design by subtracting extraneous resistors. Shown in Figure 3 is a simulation of the LED voltages in relation to the resistance of the thermistor. The plot that is high at 1k is the voltage of the red LED, and the plot that is high from 1.5k to 10k is the voltage of the green LED. As the graph shows, the LEDs begin to transition between on and off at nearly the same time. In the actual circuit this transition happens instantaneously, allowing the indicator to quickly switch once the thermistor reaches the correct temperature.

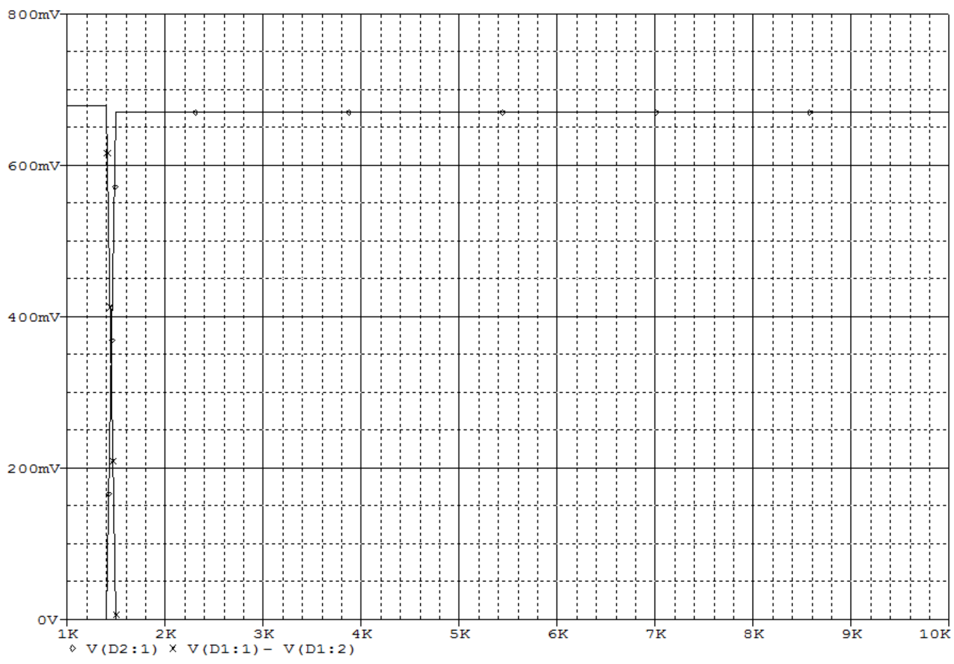

Figure 3: PSPICE LED Simulation

Once our circuit was built, we used KiCad to produce a circuit board. This design allowed us to figure out the size of the final product that would be needed, as well as confirmed that we would be able to decrease the price of the circuit board by using a single sided design, shown in Figure 4.

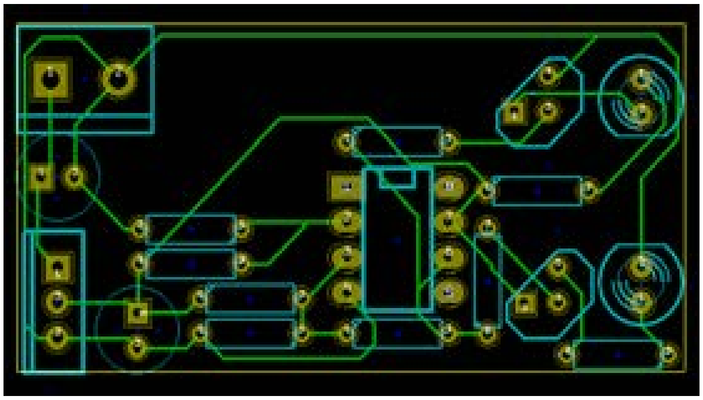

Figure 4: KiCad PCB layout

To construct the prototype, we first laid out the circuit completely on a breadboard. Beginning with the power supply system we attached an adjustable power supply and multimeter and tested if the system was able to operate properly even when voltage fluctuated. Once the power supply was set up, the operational amplifier, resistors and thermistor were connected, and a heat gun was used to see if the operational amplifier would be triggered as it heated up. Finally, the light emitting diodes and transistors were attached, and the heat gun was used to make sure that the correct LED would be illuminated when the thermistor was heated. Once the breadboarded circuit was completed, a circuit board was milled out of a single sided fiberglass board, using a woodworking v-bit to separate the copper into traces. The correct components were soldered on, and the system was tested as a whole. The circuit prototype is shown in Figure 5.

Figure 5: Circuit Prototype

After doing some research into the average temperature of running car engines, we decided that the temperature that we wanted to trigger the alarm at was 90°C. Because the triggering temperature of the alarm is determined when the resistance of the thermistor drops below the resistance of the potentiometer, we needed to figure out what the resistance of the thermistor was at 90°C. To heat the thermistor quickly, we used an Ungar 1095 heat gun, and a National Instruments thermocouple to measure the temperature of the thermistor. The thermistor was connected on extension leads to allow for easy positioning with the thermocouple, and the two were held directly over the output of the heat gun, as shown in Figure 6.

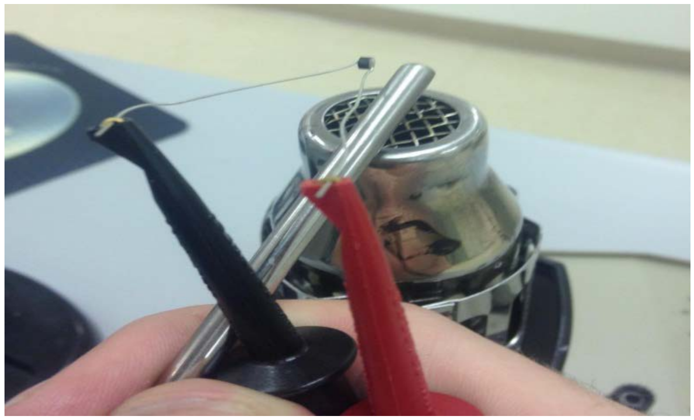

Figure 6: Testing Thermistor for the Overheating Car Alarm Circuit

Cost Analysis

In this section the cost analysis of 100 circuits is presented according to the business proposal. The primary source for our electronic components is DigiKey, which we chose due to their large selection of electrical components, as well as their low prices. For our circuit boards, we chose PCBCart, because they had the ability to customize the circuit boards ordered, as well as the ability to order a single sided circuit board to save on money. Because cars typically already have a temperature sensor built into them, we decided to make our product a kit. This means that the end user is responsible for assembly, and will allow us to save on the packaging of the product. The total cost of designing the circuit, listed as engineering time above, was acquired through the average was the average wage of an electrical engineer according to BLS.gov. Concerning the low cost of packaging containers, we assume the cost to be approximately $1.00 per unit. For the assembly of the product, through our own construction it takes approximately thirty minutes to put together a single circuit, adding up to fifty hours total for the total 100 PCBs.

The cost of the factory labor was obtained through BLS.gov, with the labor cost being the national minimum wage. The factory supplies that we calculated was $200 for a soldering iron to assemble the final circuit board. Adding up these sum costs leads to a total of $1575.74, or $15.76 unit price. From here we set up a markup of $4.24 to make a total profit of $424.00 from the 100 circuits. On the terms of delivery, the circuit PCBs must first be assembled through PCBcart, which requires 12 days of machining and assembly, from their regular shipping requires two additional days, meaning the total amount of days for the PCB to be shipped is 14 days. The low initial investment, having PCBcart manufacture the circuit for us, means that the breakeven point is reached as soon as the first circuit is sold. The bill of material is shown in Table 1 and cost analysis is in Table 2.

Table 1: Bill of Materials

Part Number	Description	Quantity	Unit Price	Extended Price
296-11107-5-ND	Operational Amplifier	100	0.35100	$35.10
365-1189-ND	5mm Red LED	200	0.13000	$26.00
NCP7805TGOS-ND	5V Linear Regulator	100	0.29340	$29.34
P5178-ND	10uF Capacitor	100	0.06800	$6.80
P5165-ND	100uF Capacitor	100	0.09750	$9.75
CF14JT1K20CT-ND	1.2kΩ resistor	100	0.02190	$2.19
CF14JT10K0CT-ND	10kΩ resistor	300	0.01624	$4.87
1.0MQBK-ND	1MΩ resistor	100	0.02470	$2.47
CF14JT1K00CT-ND	1kΩ resistor	100	0.02190	$2.19
2N3904D26ZCT-ND	NPN Transistor	100	0.12050	$12.05
2N3906-APCT-ND	PNP Transistor	100	0.11120	$11.12
CF14JT100RCT-ND	100Ω resistor	250	0.01624	$4.06
RL1005-5744-103-D1	10kΩ Thermistor	100	0.99370	$99.37
Single Sided PCB	25mmX50mm	100	0.74 + 29.13 tooling	$103.13
			Sales tax (8.25%)	$20.24
			Total Cost	$368.68
			Unit Cost	$3.69

Table 2. Cost Analysis

Description	Individual Cost	Total Cost
Electrical Components	$3.69	$368.68
Engineering Time	12 hours at $42.88 per hour	$514.56
Packaging	$1.00	$100.00
Factory Assembly	50 hours at $7.85 per hour	$392.50
Factory Supplies	Soldering iron	$200

	Total Cost	$1575.74
	Unit Cost	$15.76
	Markup	$4.24
	Sale Price	$20.00
	Total Profit	$424.00

Conclusion

The end result of our project is a circuit that is easily capable of determining when a temperature value is above the specified level, and alerting someone when it reaches that point. This circuit can have a specific value in testing or monitoring specific parts of a car engine, the car radiator for example. Through research, experimentation and design using PSPICE and KiCad, our group has created this circuit and found it to be an effective solution to the presented problem. Through using cheap online component suppliers, purchasing in bulk, as well as finding a company online that can mill and assembly the PCBs at a relatively low cost, we have found our circuit to be both profitable and competitive in today's market.

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