Developing a Customer Appropriate Value Proposition: A Student Project Delivering a Temperature Sensor to Meet Customer Specifications

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Abstract

This paper describes the results of a student-led project from an undergraduate course in electric circuits. The project required students to organize into interdisciplinary teams consisting of two to four members with the task to design and construct a temperature sensor. Each group represented a fictitious company that was invited to participate in a Request for Proposal (RFP) from a fictitious customer who was looking to purchase a quantity of temperature sensors. While the task was to design and construct a temperature sensor, the ultimate goal was to successfully pitch the product and its design to win the bid. The fictitious companies were vetted through a two-stage bidding process. The first stage required the submission of a working prototype along with a written proposal including the technical details of the design, bill of materials, testing plans and procedures, and a breakeven cost analysis. After submitting the proposals the "companies" pitched their proposals to the customer, which was the section instructor, with a PowerPoint poster as a visual aid. The winners of the first stage from the three sections of the electric circuits course then competed in a second pitch. In preparation for the second pitch, the students received feedback from their respective section instructor, and made modifications to improve the design, testing procedures, and pitch. This paper presents the details of the designs and overall approaches taken by the two best "companies" from the contest. After presenting the different approaches, some discussion is dedicated to comparing the similarities and differences of the approaches along with the merits of each approach.

Introduction

Within the College of Engineering at Ohio Northern University (ONU), the electric circuits course serves students from electrical, computer, mechanical, and civil engineering, as well as engineering education students. Due to its diverse composition in terms of engineering disciplines, the electric circuits course offers faculty an excellent opportunity to offer interdisciplinary projects with technical depth yet which also provide students with a perspective on the importance of entrepreneurship in engineering[1,2,3]. This paper describes the work of the two best student groups from a project offered in the Fall 2013 semester, which required students to develop a customer appropriate value proposition concerning a product designed by the students. The initial offering of the project, given in Fall 2012, has been described in another paper[4].

The project required students to organize into interdisciplinary groups of two to four members with each group comprised of students from at least two different disciplines with the task to design and build a temperature sensor. Each student group represented a fictitious company invited to participate in a Request for Proposal (RFP) from a fictitious customer looking to purchase an initial order consisting of 100 temperature sensors. The RFP required each company to submit a written product proposal and to pitch their product to the customer using a PowerPoint poster as a visual aid. The written proposal included a bill of materials (including the cost of each component in the circuit), cost analysis (including design overhead and any labor in a break-even analysis), circuit design and simulation (with specific, real-world components), testing plan (for the initial purchase of 100 temperature sensors), layout of PCB and packaging schematic, delivery time, and the voltage-temperature characteristic of the circuit. Additionally, each group fabricated a prototype on which to perform specific tests from the test plan as a proof-of-concept.

In the design phase of the project, each group developed two alternate designs for the temperature sensor to meet the customer specifications. The customer required that the temperature sensor incorporate a Negative Temperature Coefficient (NTC) thermistor and output a 0 to 5 volt signal for the temperature range of 25˚ to 50˚C, respectively. Given these customer constraints, the final design selected by each group was based on criteria ranging from the number of batteries required (and other power considerations), to the number of components required (and the overall cost of the circuit).

The bidding process was broken into two stages. The first stage was a contest among the "companies" within each of the three sections of the course and the winning groups from the first stage competed in a second pitch contest for the winning bid. The members of the top group from each section were allowed to meet with their section instructor prior to the second pitch in order to improve their design, testing procedures, and pitch. Based on the results of the second stage (obtained from rubrics developed for the pitch, written proposal, and poster), two "companies" tied for the overall bid: Mr. Thermistor and LBK. In this paper, the deliverables of these two "companies" are described by the students, along with a detailed comparison of the different approaches to design, testing, and the business aspects of the project.

Project Description Given to Students

Design a temperature sensor that operates in the range of 25˚ to 50˚C, and uses a *thermistor*, which is a variable resistor whose resistance value varies significantly with temperature. The thermistor you are to use in your design is made by GE and is a Negative Temperature Coefficient (NTC) thermistor, which means that the 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:

$$\beta = \frac{\ln\left({}^{R}/_{R_0}\right)}{{}^{1}/_{T} - {}^{1}/_{T_0}} \tag{1}$$

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 (which includes the operating range for the temperature sensor). 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.

The customer plans to use your temperature sensor circuit with a microcontroller that accepts a voltage in the range of 0 to 5[V] in order to close the loop and turn on some fans to dissipate heat based on the temperature. In order to design the control law to be implemented in the microcontroller, the customer needs the voltage-temperature characteristic of your temperature sensor circuit. The only specified guidelines are to make sure the output voltage is 0[V] at a temperature of 25˚C, and 5[V] at a temperature of 50˚C.

Deliverables:
There are five parts to the project:
- (i) 1-2 page alternative design solution document,
- (ii) 5-10 page written proposal,
- (iii) Circuit prototype with specification sheet (attach to proposal)
- (iv) 5-minute pitch during which the company will try to sell its product using a
- (v) poster made using PowerPoint (each company will project the poster during the pitch competition).

Approach of Mr. Thermistor

The goal of Mr. Thermistor for this project was to provide a high quality, inexpensive circuit board to the customer in a timely and efficient manner. In the following sections we describe the business model and organization of Mr. Thermistor, the technical details of the two alternate circuit designs along with simulation results for the final design, the details of the prototype construction and testing methods, and a breakeven cost analysis.

Business Model and Organization

In order to achieve maximum efficiency the team decided to organize the fictitious company, Mr. Thermistor, as a large circuit board design company and manufacturer with assembly lines equipped with industrial robots. There are many benefits to organizing the company in this way. First, the company is able to construct any type of circuit board the customer desires quickly due to the assembly lines. Second, the industrial robots reduce the total number of employees, which in the long term helps keep costs low for both the customer and the company. Third, the company is able to quickly construct a large quantity of circuit boards for any customer, which increases the target market to include small, medium, or large orders from clientele. Finally, being a large circuit board design company and manufacturer allows Mr. Thermistor to harness economies of scale and order the electrical components needed to construct circuit boards in bulk at a lower cost.

Once the team decided the size and scope of Mr. Thermistor, we started working on the details of the business model and organization. It was decided that Mr. Thermistor has one headquarters, which is the largest facility and produces the greatest number of circuit boards. There are several other smaller facilities spread out regionally to distribute the workload, reduce shipping costs and delivery time, and to reach out to different regions of the country. The company has a website to advertise its capabilities, and it relies on a series of advertisements and business connections to obtain contracts for the design and production of circuit boards. After products are made they are usually packaged in the factory and stored in a warehouse adjacent to the factory. Then the company ships the products using various regional shipping companies that offer the best rates in the given region. Overall, Mr. Thermistor is a well-established company with many different locations around the United States and has a good reputation as a circuit board design company.

With regards to the RFP described in the project, the company was tasked with designing and building 100 circuit boards as a trial run for a customer, which is a small order for Mr. Thermistor. Being a larger circuit board design company influenced the way that Mr. Thermistor approached the proposal. For such a small order, Mr. Thermistor was not overly concerned with obtaining a large profit from this contract. Instead, the bid was viewed as an opportunity to create a good relationship with a new customer. It was stated in the RFP that this bid was a trial order so that the customer could find the best product to buy in bulk. For this reason, Mr. Thermistor looked to minimize the cost of the circuit board.

Another factor affected by the small size of the order was the amount of labor required. Although the assembly lines were fully automated, the company still needed an electrical engineer to design the circuit for the customer and set up the equipment to manufacture the boards. The electrical engineer would only need about 3 hours in order to produce the design and set up the manufacturing equipment, which is far less labor time than a smaller company would need.

The team decided to use UPS for shipping the 100 circuit board order because it is the least expensive method for a small shipment, rather than using a shipping company that specializes in larger orders. Overall, the team looked at this 100 circuit board order as a chance to establish a potential partnership with a new customer.

Circuit Design and Simulation

Mr. Thermistor had two designs that both met the customer specifications. The first design was a very basic design consisting of four resistors, one thermistor, and an operational amplifier (or just op amp). The second design, which was the final design, was slightly more complex. This design had a total of ten resistors, one potentiometer, two op amps, and one thermistor, and is shown in Figure 1 (with the potentiometer modeled as the two 500Ω resistors and the thermistor has temperature-dependent resistance R_T).

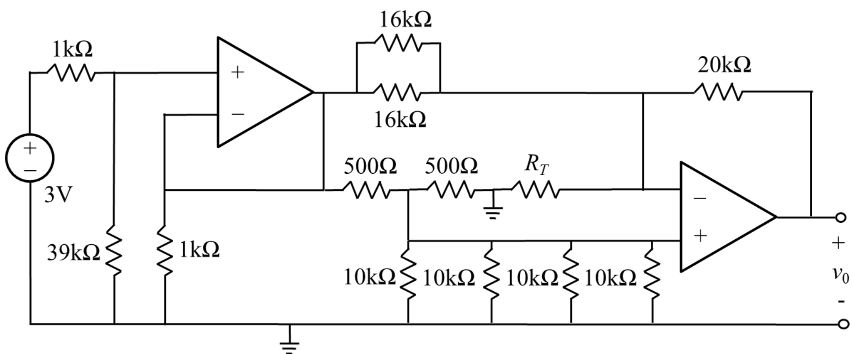

Figure 1: Final circuit design of Mr. Thermistor

The first op amp and set of resistors acted as a buffer, and set the voltage at the output of the first op amp at 2.925[V]. A 1kΩ potentiometer was used in the second stage and adjusted so that there was 500Ω resistance between the middle terminal and either of the end terminals. The two parallel 16kΩ resistors are used to create an equivalent 8kΩ of resistance, and four parallel 10kΩ resistors are used to create an equivalent 2.5kΩ of resistance. Using standard ideal op amp analysis[5], it can be shown that the relationship between the thermistor resistance R_T and the output voltage v_0 is given by

$$v_0 = \frac{26590}{R_T} - 2.65925$$

Since the thermistor model used has a nominal resistance of 10kΩ at 25°C and the resistance at 50°C can be determined using (1) to be 3475Ω, the output voltage is -0.25mV at 25°C and 4.99255V at 50°C. The operational requirement of the customer was for the output voltage to be zero volts whenever the ambient temperature was 25˚C and five volts whenever the ambient temperature was 50˚C. Therefore, the final design is within 0.2% error of the customer specifications.

The simulation results from the final design met the customer specifications with less than 1% error, and are shown in Figure 2. The simulation results show that the design chosen would go from 0V to 4.99255V within the temperature range 25˚ to 50˚C, respectively.

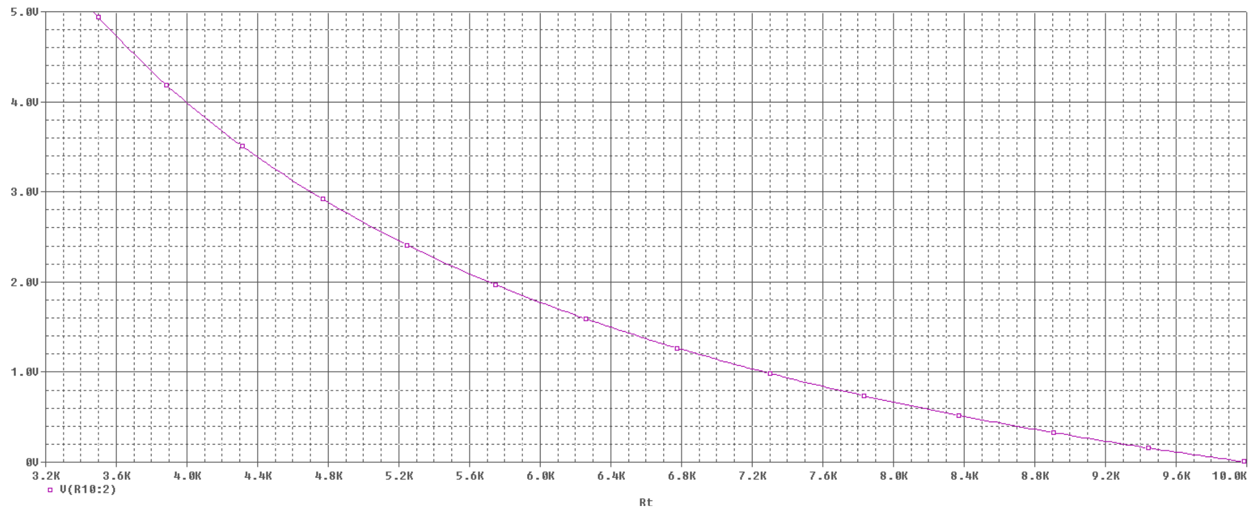

Figure 2: Simulation of Mr. Thermistor's final design showing output voltage vs. thermistor resistance

Prototype Construction and Testing

Constructing the circuit board prototype was a relatively simple process. We initially designed a circuit on PSPICE, and then made a wiring schematic and gave it to the electronic technician employed at the university, Brad Hummel. Brad constructed a circuit board and gave it to us for soldering. We found all of the various components needed for the circuit board, including a potentiometer, thermistor, two operational amplifiers, and various resistors. We checked the value of all the resistors before soldering them onto the board. After that, we wrote down the approximate resistor value, and sorted them by resistance. Finally it was time to start soldering all of the pieces to our circuit board. This was a three-person process. One person operated the soldering iron, while another individual looked over the wiring schematic and called out the next component needed for the given location. The third person handled the components and gave the correct part to the person operating the soldering iron, while looking at the PSPICE diagram to verify correct values. Overall, circuit construction went very smoothly, with only a few minor errors, which were fixed immediately.

After the components of the circuit were soldered to the board, we began testing. We initially tried using the heat of the soldering iron near the thermistor, but found we could not get a consistent temperature read out on the thermometer. Then we decided to use a heat gun. We held a thermometer next to the thermistor, and measured the temperature of the air blowing on the thermistor. We were able to attain varying temperatures that were relatively constant by changing both the distance between the heat gun and the thermistor, and by changing the speed at which the air was forced out of the gun.

We wired the thermistor up to a digital multimeter, which was capable of reading the output voltage of the circuit board. Initially we tested the circuit at 25^{o}C, and measured the output voltage of the circuit. Then we increased the temperature of the air at the thermistor by increments of 2.5^{o}C all the way up to 50^{o}C, measuring the output voltage of the circuit board along the way. The data from testing is illustrated in Figure 3 and the prototype (set up for testing) is illustrated in Figure 3.

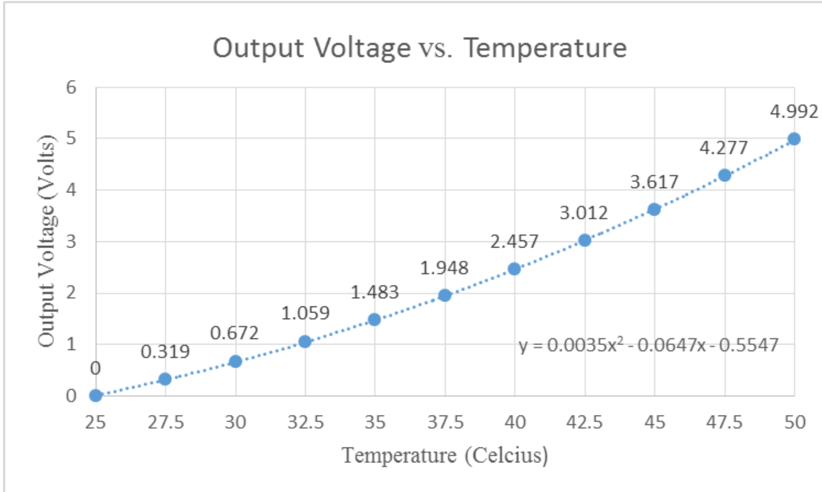

Figure 3: Testing results of Mr. Thermistor

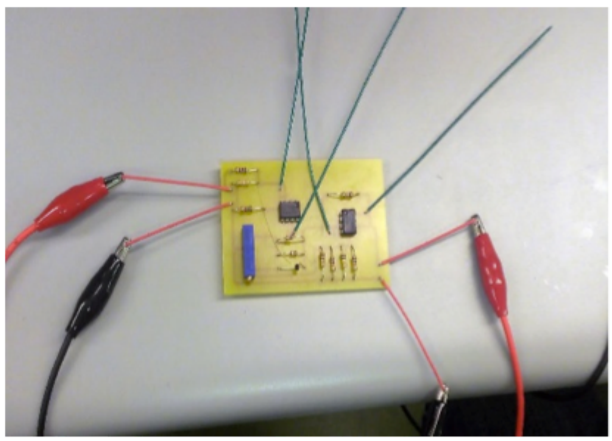
Figure 3: Prototype of Mr. Thermistor prior to testing

After successfully verifying that the circuit prototype satisfied customer specifications, the order was in a position to be completed, assuming the bid was awarded to Mr. Thermistor. The plan for packaging was to use a box large enough to fit several temperature sensors in a single box. Each individual temperature sensor would be encased in bubble wrap to ensure that there would be no damages in transportation.

Cost Analysis

The cost of a product is often as important as its functionality. At Mr. Thermistor, we understand this need and have worked to ensure that our design meets the financial needs of the consumer. As a well-established company, Mr. Thermistor offers many benefits that other companies cannot. One of the most significant benefits is our circuit-production equipment. This equipment, designed by skilled electrical and mechanical engineers and operated by efficient technicians ensures that our product is produced in a timely manner with pleasing quality control levels. It is through this equipment that we are able to keep production costs low, quality high, and pass savings on to the consumer.

An additional benefit of working with Mr. Thermistor is our access to industry-leading suppliers. Due to the current volume of product in which we deal, the additional materials required to produce the requested one hundred temperature sensor units are easily acquired. Furthermore, Mr. Thermistor can purchase supplies at quantity-discounted rates, lowering the cost of the finished product.

Each temperature sensor is comprised of fifteen separate components. Table 1 details the cost of each component as well as the total materials cost for the product.

Table 1: Material Costs

Part	Number of parts	Cost per unit ($)	Cost per 100 units ($)
Resistor	10	0.06*10= 0.60	60.00
Potentiometer	1	0.30	30.00
Op Amp	2	0.26*2= 0.52	52.00
Circuit board	1	1.00	100.00
Thermistor	1	0.21	21.00
	Total	2.63	263.00

Based on the description in the RFP, which stated that the temperature sensor would interface with a microcontroller, it is assumed that the temperature sensor will be powered either by the microcontroller or from some other external power source already available to the customer. As such, the cost of batteries (or other dedicated power supply) is not included. It is expected that the prices quoted in Table 1 may vary slightly, but would likely be lower should the desired quantity be increased.

The cost of materials makes up the majority of the cost of the temperature sensors. However, there are other associated costs. Mr. Thermistor anticipates that the design and production of the circuits will only take three hours due to our skilled staff and modern equipment. This will require three hours at our engineer's pay rate of $32 per hour, $5 worth of utilities (electric), as well as a one-time consulting fee of $9, to be added to the total price. Mr. Thermistor plans to ship all one hundred requested circuits in the same package using the United Postal Service (UPS) at a rate of $9.73. Given all of these additional costs, Mr. Thermistor has determined that a reasonable price per unit is $4.99. Break-even analysis, with the data illustrated in Table 2, reveals that the first twenty-six units are sufficient to cover all costs and therefore a profit is made on the remaining seventy-four units.

Table 2: Breakeven Point and Profits

	Expenses ($)	Cost per unit ($)	Price per unit ($)	Profit ($)
1 unit	43.63	43.63	4.99	-38.64
26 units (breakeven)	129.74	4.99	4.99	0
50 units	211.50	4.23	4.99	38.00
100 units	382.73	3.83	4.99	116.27

The total profit for Mr. Thermistor will be a reasonable $116.27 for the entire order of one hundred temperature sensors. If the customer is interested in ordering a larger number of sensors, the price per unit will be negotiable.

Approach of LBK

Business Model and Organization

We took the position that LBK is a small engineering design firm owned by the group members and operated as a partnership. The partners also serve as design engineers for the firm and take on the design portion of projects such as the one described in the RFP. The manufacturing of the designs is contracted out. For circuit designs, construction is contracted to an electronic technician. This business model has the benefit that while the designs are being manufactured, the partners can continue research and development on other projects.

Circuit Design and Simulation

When it came to designing a circuit for this bid, it was clear that using some sort of op amp configuration would allow for the best control of an output voltage with a thermistor. The first (alternate) design that was created was a single op amp design in which the op amp functions as an inverting summing amplifier[5]. This means that the output of the op amp is given by

$$V_o = -R_f\left[\frac{V_1}{R_1} + \frac{V_2}{R_2}\right] \tag{2}$$

where V_1 and V_2 are input voltages, R_1 and R_2 are connected in series with the input voltages V_1 and V_2, respectively, and R_f is the value of the feedback resistor with the op amp connected in a negative feedback configuration (see Figure 4).

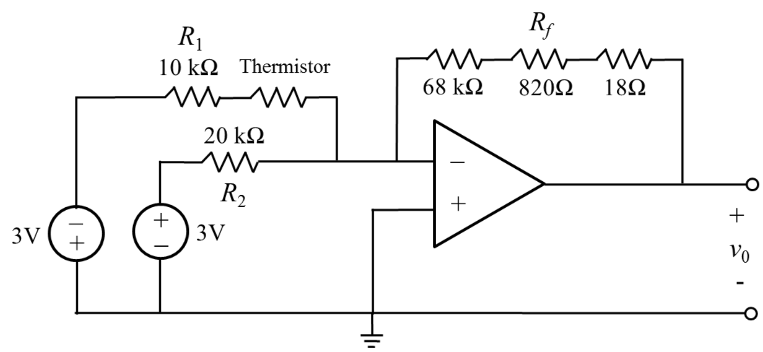

Figure 4: Alternate design of LBK

To determine the parameters of this configuration to satisfy the customer specifications, the two boundary cases (25°C and 50°C) are examined. For the output voltage of the op amp to be zero volts at 25°C, the ratio of V_1/R_1 has to be the same magnitude as V_2/R_2, but one of them has to be negative. To achieve this we set both voltage sources to three volts but with opposite polarity, as shown in Figure 4. The resistance of the positive voltage source is set equal to the resistance of the negative voltage source at 25°C, which had the thermistor. Since the given thermistor has a nominal resistance of 10kΩ at 25°C, resistors R_1 and R_2 are selected to be 20kΩ and 10kΩ, respectively.

In order for the output of the op amp to be 5 volts at 50°C, the resistance on the negative voltage source must be less than the resistance on the positive voltage source to get a positive value. Given that the B-constant for RL1005-5744-103-D1 thermistor model is β = 4073[K], the resistance of the thermistor at 50°C can be determined to be 3475Ω by using (1). Therefore, the only parameter left is the value of the feedback resistance R_f (which is the sum of the three series resistors in Figure 4). To determine the necessary value of R_f equation (2) is solved for R_f, which results in 68,838Ω. Once the values were calculated the design was simulated in PSPICE using a variable resistor to represent the thermistor, with the resistance ranging from 3475Ω at 25°C to 10kΩ at 50°C. The results of this simulation are shown in Figure 5.

In the second (final) design, illustrated in Figure 6, there are two op amps and each accomplishes separate goals based on the configuration of the resistors around the op amp. The first op amp that has an input voltage of 1.5 volts is a non-inverting op amp[5], which is used to amplify the input voltage as described by the equation below:

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_1 \tag{3}$$

where V_1 is the input voltage, R_1 is the resistance in series with the input voltage, and R_f is the feedback resistor. The second op amp used in this configuration is a differencing op amp[5] governed by the equation

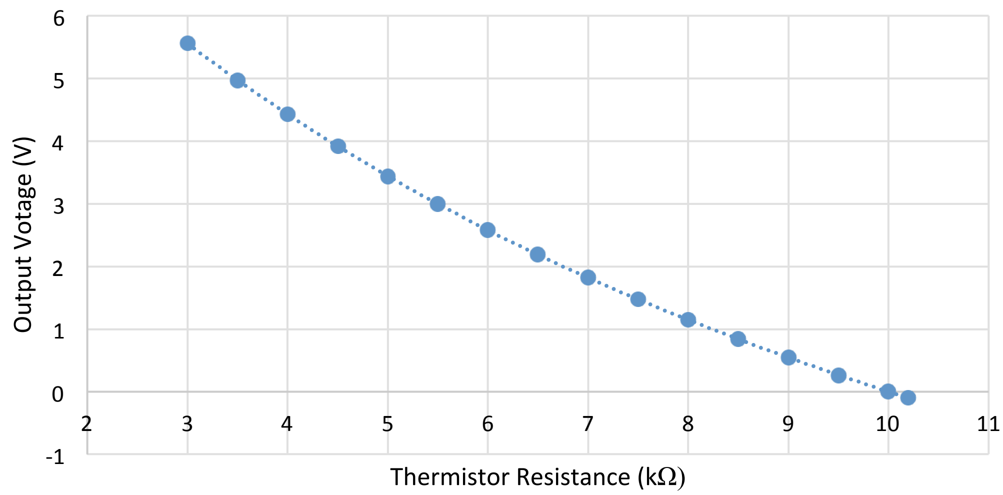

Figure 5: Simulation results for the alternate design of LBK

$$V_o = \frac{R_f}{R_1}(V_2 - V_1) \tag{4}$$

where V_1 and V_2 are the input voltages, R_1 is the (common) resistance in series with each input, and R_f is the feedback resistor.

Given these equations and the choice of parameters shown in Figure 6, the output voltage of the first op amp stage is 3V whenever the thermistor is at 25°C, and the output voltage of the second op amp is 0V. Whenever the thermistor is at 50°C, the output voltage of the first op amp stage is about 2V, which makes the output voltage of the second op amp is 5V. This design was also simulated using PSPICE to show that it matches the customer specifications. The simulation results are shown in Figure 7.

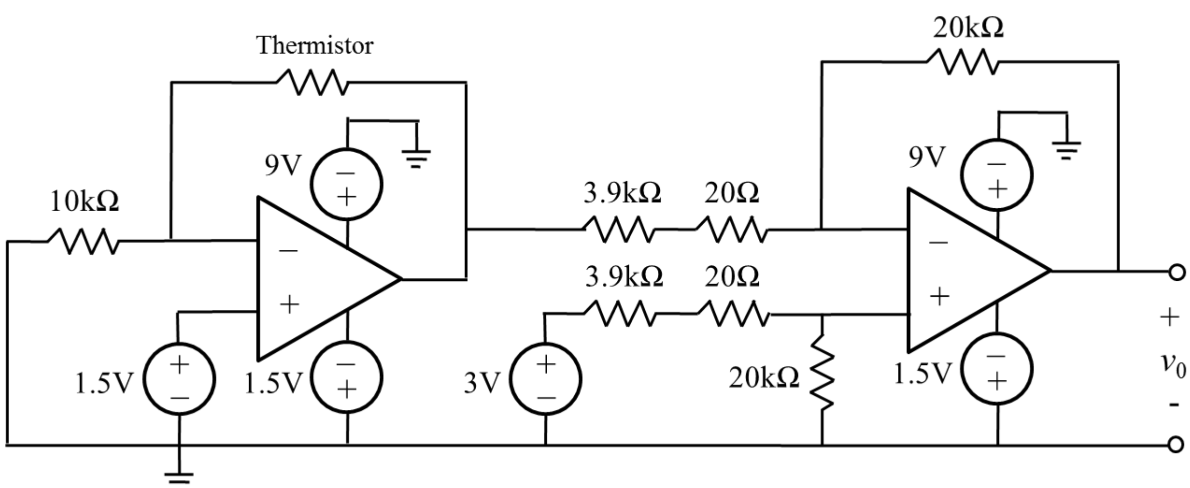

Figure 6: Final design of LBK

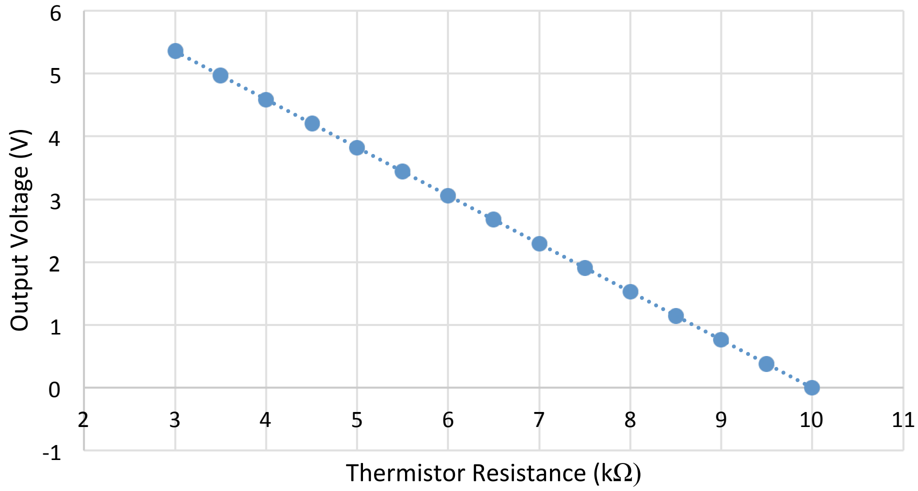

Figure 7: Simulation results for the final design of LBK

Prototype Construction

A prototype was constructed to demonstrate that the circuit was viable. The members of LBK designed the PCB layout, and passed the layout to Brad Hummel for fabrication. Once the traces on the board were laid out, the components, including LM741 op amps and standard carbon-film resistors, were soldered onto the board. LBK had offered two available options to the bidder; one model with a standard 10-kΩ resistor and one model with a 20-kΩ potentiometer to allow for calibration. The model with the 20-kΩ potentiometer was assembled for prototype testing

LBK assumed that the circuit needed to be self-powered, so the circuit was packaged with batteries. An analysis of the power consumption and battery life was done using a model for battery decay for AA alkaline cells whenever the discharge rate is 100mA[6]. The performance of the circuit under battery decay was simulated in PSPICE and the output voltage was observed. According to the PSPICE simulation, the circuit drew 125μA from the AA batteries. To determine the useful lifespan of these batteries, an output error of 3.5% at the largest voltage of 5V was considered to be acceptable, which occurs whenever the voltage of the AA batteries drops to 1.45V. Therefore, based on the model of battery decay, the useful lifespan of the batteries was 0.1Ahr, which given the current drawn from the batteries results in approximately 800 hours of useful life. The overall power consumption of the circuit was approximately 13.5mW.

During this simulation process it was discovered that if a 20-kΩ potentiometer was used instead of the original 10-kΩ potentiometer, then the potential usable battery life was greatly increased by making adjustments to the potentiometer. By calibrating the potentiometer, the battery life of the AA-batteries was increased from 33 days of continuous run time to 396 days of continuous runtime. The usable life of the 9-V battery that powered the op amps was calculated to be 16 days of continuous run time. The life of the 9-V battery was determined in a similar fashion based on the model of battery decay at a discharge rate of 100mA[7]. According to the PSPICE simulation, the circuit drew 1.19 mA from the 9V battery and the battery was useful until it decayed to 5.15V. Based on the model of battery decay, the 9V battery was determined to have a useable lifespan of 0.45Ahr, which given the current drawn from the battery results in approximately 380 hours of useful life. The overall power consumption of the circuit was approximately 13.5mW.

Testing

In order to test the circuit experimentally the prototype was subjected to varying temperatures using a heating pad. The instantaneous temperature of the heating pad was determined using an alcohol thermometer. To test the circuit, the thermistor probe and thermometer were wrapped in the heating pad, as illustrated in Figure 8, and a multimeter probe was attached to the circuit's output node. The heating pad was turned on and the temperature of the heating pad increased. As the system heated, the temperature was read from the thermometer and recorded along with the output voltage of the circuit. The results of the test are tabulated in Table 3, and illustrated in Figure 9. The data does not correspond well to the predicted values between 25^{o}C and 50^{o}C; however, the data does match the predicted values for temperatures close to 25^{o}C and 50^{o}C. This can be explained by the differences in the time constants of response for the thermistor circuit and the thermometer. Another reason for experimental error was variations in the temperature of the heating pad. The location of the heating coils in the heating pad was not taken into consideration in the experiment. When the system is reaches steady state, the data is in agreement as it is at 25^{o}C and 50^{o}C. Checking the experimental data against theoretical values yielded 0.2% error at 26^{o}C degrees and 0.5% error at 49.9^{o}C.

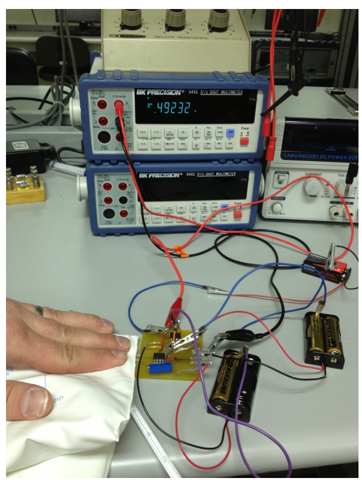

Figure 8: Experimental setup for testing by LBK

Table 3: Experimental results of LBK from testing

Temperature [^{o}C]	26	26.9	28.2	32	35	40.5	42	43	48.2	49.1	49.9	50
Output Voltage [V]	0.34	0.38	0.522	0.772	0.86	2.16	4.6	4.7	4.66	4.87	4.95	5.14

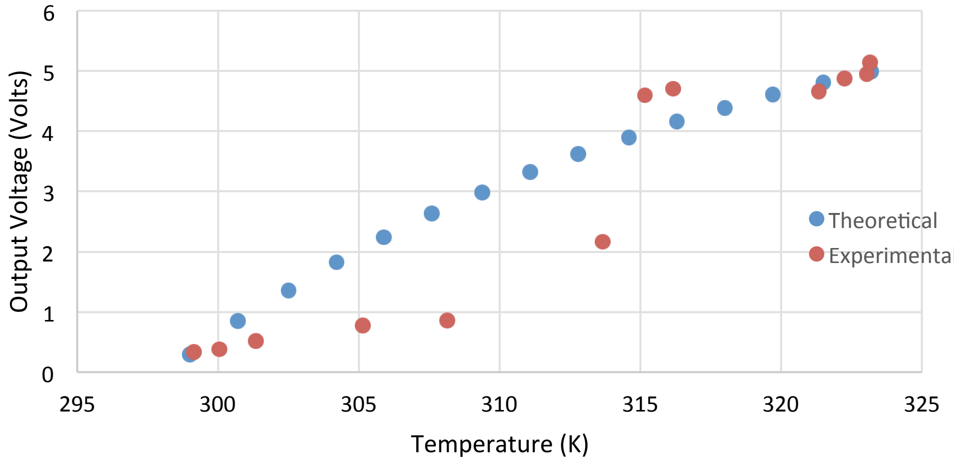

Figure 9: Comparison of measured and theoretical output voltages

Cost Analysis

Profit is the single greatest driving force behind a company. LBK plans to make a profit from the product after only one month. To determine how many units must be sold to begin making a profit, breakeven analysis is used. The breakeven point is found by solving (5), which is the breakeven equation[8].

$$\text{Breakeven point} = \frac{\text{Fixed costs}}{\left(\frac{\text{Price}}{\text{unit}}\right) - \left(\frac{\text{Cost}}{\text{unit}}\right)} \tag{5}$$

Usually the price of the product is identified, and then the number of units to break even is calculated (i.e., the breakeven point). However, instead of determining the breakeven point based on a given per unit price, we preferred to set the number of units to break even and solve for the necessary per unit price. Based on the assumption that the technician can fabricate 640 units per month, we set the breakeven point so that we would begin making a profit after one month (or 640 units). The fixed costs were evaluated at $4000 per month. This value comes from the total income for the hours spent developing the product, as well as the hours the technician spent on fabrication, which is broken down as follows. Between the three members in the company, at an hourly wage of $40, the three partners of LBK would make a combined $800 based on 20 hours of billed design hours. The technician however, would make $20 per hour, with a monthly total of $3200. This total was developed by assuming the technician worked for 8 hours a day, five days a week for four weeks a month.

Once the breakeven point and fixed costs were determined, the final value needed is the cost per unit. This was determined by researching the price of each component of our design. A bill of materials for each configuration was developed using the prices that were found for each component. We then solved for our per unit price using (5). Because there were two different configurations of the product, there were two separate costs per unit. The material cost of making this product using a potentiometer was only $9.41. This was higher than the cost of producing the same product with a 10 kΩ resistor, which could be produced for $6.79.

By hiring a skilled technician to create the product at a lower hourly wage than ourselves, we were able to keep the selling price calculated in the breakeven equation less than double the price of the product. Using the equation, we found that the selling price to breakeven after only one month was \$19.79 using the potentiometer configuration, while the selling price of the resistor configuration was found to be \$14.24. The alternative approach we applied to the breakeven analysis allowed us to make a profit after only one month.

Packaging and Shipment

We were also able to minimize costs and effectively deliver our components by developing a simple method for packaging. Once our products are complete, we simply place them in a box, alternating layers of bubble wrap with the product. The compactness of this configuration minimizes the amount of bubble wrap and the number of boxes needed to ship an order. This reduces the shipping costs.

For this particular assignment of 100 items, we assumed that our technician would complete the order in less than four days. This means he would have the remainder of the fourth day to package the shipment. We are able to have an order of 100 units placed on Monday and have every circuit completed by Thursday, with packaging and shipment done by Friday.

Comparison of Approaches and Conclusions

For the project, both teams were required to create a fictitious company to manufacture and sell the designs of the temperature sensor. Each team's company was different in terms of their business organization and the way they constructed the circuit boards. The first team's company, Mr. Thermistor, was organized as a large-scale company with automated assembly line equipment. Mr. Thermistor was able to quickly and efficiently manufacture any size order that was received from a customer. The second team's company was named LBK, which was set up as a smaller free-lance engineering design firm that specialized in custom circuit boards. LBK designed and manufactured circuit boards manually based on the orders they received from customers. The way the teams portrayed the companies are vastly different which caused many other things to vary between the two companies.

One aspect that was different between the two companies was the labor cost that went into making the circuit boards. The approach taken by LBK required more skilled labor time than Mr. Thermistor, who had most of the production process automated. So ultimately LBK's labor cost was higher. Another difference was in how the circuit would be powered. Mr. Thermistor designed their circuit to be integrated into an existing system, from which it drew power. Conversely, LBK designed their circuit to be a stand-alone unit that relied on battery power. This led to very different analysis techniques. Mr. Thermistor's analysis focused entirely on the circuit's performance whereas LBK's analysis considered both circuit performance as well as power consumption and battery life.

Additionally, the financial analysis of each circuit was very different due to the different power assumptions. Mr. Thermistor had a low cost per unit due to their assumption that batteries would not be used, and therefore would not contribute to the price of their circuit. LBK, however, included the price for batteries in their analysis. This increased the price per unit dramatically, despite the fact that the circuit components themselves, other than the batteries, were very similar in both designs. Ultimately, LBK priced their units at $19.79, while Mr. Thermistor priced their units at $4.99, nearly a quarter of the cost.

Some similarities of the circuit board designs that the teams built were what type of parts they used, and the accuracy of the designs. The circuits were required to use a thermistor in order to achieve the correct amount of voltage at both temperatures, and both teams created a circuit board that used two op amps and a potentiometer. For both teams, the first op amp was used as a non-inverting op-amp and the second op amp was used as a differencing op-amp. The potentiometer was used in both circuits in order to tune the values of resistance and voltage that the circuit would output. Using these parts caused each team's circuit board to be very accurate and output as close to 5V as possible.

Finally, the testing procedures done by each group had some similarities and differences. Both groups tested the product by applying a heat source to the thermistor while measuring the output voltage using a multimeter. However, two distinct differences between the two groups can be identified. The first difference is that the LBK group used a heating pad or just the heat generated between the fingers to produce the heat. This led to only a few accurate data points near the two-endpoint values of 25^{o}C and 50^{o}C. Mr. Thermistor supplied the heat using a heat gun and varied the temperature across the entire range of possible temperatures. Although the testing was different, both groups agreed that during large-scale production, both companies would test many more samples than just one.

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