University of Connecticut

Department of Electrical and Computer Engineering

ECE 4902: Fall 2017 – Spring 2018

Team 1817 (Hubbell):

Electrical Plug, Connector, and Receptacle temperature sensor

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Introduction

The electric plug, connector, and receptacle temperature sensor project is sponsored by Hubbell Wiring in Shelton, CT. Hubbell is the manufacturer of Twist-Lock plugs, connectors, and receptacles. The project goal is to optimize a temperature sensing system by miniaturizing a sensor array. These sensors will need to communicate with a microcontroller to transmit temperature information.

Background

Temperature sensors have been in industry applications for maintaining a specific temperature for equipment. These component are essential to thermal protection and monitoring. There are various types of sensor, but the most common temperature sensors used are Infrared-based sensors, Resistance Temperature Detectors, and Semiconductor-based sensors. Each type of sensor have their advantages and disadvantages based on the application, environment, and situation.

Statement of Need

Hubbell has tasked the team with researching existing temperature sensing technologies and looking to design, miniaturize, and optimize a small temperature sensing system. The design must be adaptable to different conditions; including environment and targets of measurement. The design must be able to have a flexible form factor for various implementations. There must be data interpretation built into the design to take information from multiple temperature sensors, perform any necessary computation, and output the data to the user. Overall, the goal is to optimize a temperature sensing system by miniaturizing a sensor array.

Objective

The goal of our design is to design a temperature sensor system in a 1 inch by 1 inch component density with the implementation of temperature readout. Sensors must have an accuracy within +/- 1 degree celsius and have a temperature reading range of -20°C to 80°C. This is to be done with a microcontroller that can read from multiple temperature sensors. Overall, the implementation of our final design cost should fit under our $8 USD budget.

Summary

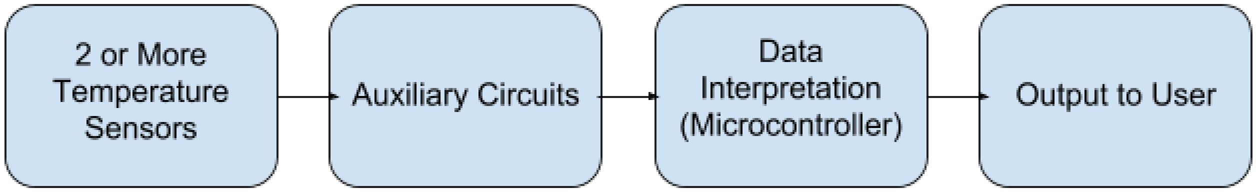

Figure 1: Solution summary

Solutions

Research has been performed into different existing temperature sensing technologies including resistance temperature detectors, infrared technology, and semiconductor technologies. The effective temperature ranges for the technologies has been examined as well as the accuracy, whether a technology is contact or non-contact measurement, and any issues associated with the technologies.

Based on the aforementioned research, two optimal technologies have been selected for implementation and testing. Resistance temperature detectors (RTDs) and infrared technologies are the optimal choices for selection to satisfy our requirements and specifications.

RTD

Background

Resistance Temperature Detectors (RTDs) measure temperature by correlating the resistance of the RTD element with temperature. To specifically measure the temperature, the Callendar-Van Dusen equation was used. The equation is given below.

$$R_t = R_o(1 + \alpha T + \beta T^2 + C(t - 100)T^3)$$

For the Temperature range of $-200^\circ C \leq t \leq 0^\circ C$, where R_t is the resistance at temperature T, R_o is the resistance at 0°C, and T is the temperature in Celsius. The constants α, β, and C are known as the Callendar-Van Dusen constants. These constants will depend on the exact RTD that is used as well as the material. For practical purposes, temperature range of $0^\circ C \leq t \leq 661^\circ C$, the equation $R_t = R_o(1 + \alpha T + \beta T^2)$ will satisfy correlation between resistance and temperature.

RTDs are generally used for close proximity purposes or in contact with the surrounding or object.The typical temperature range that they operate range from is -60℃ to 600℃. This temperature range will depend on the RTD element. RTDs provide incredible accuracy within 1℃ or better. The most common RTD composition materials are copper, nickel, and platinum.

RTDs come into two basic styles: wire-wound and thin film. Wire-wound RTDs are constructed using a wire wound around a ceramic or glass bobbin in one of two configurations: birdcage or helix. The birdcage configuration keeps the RTDs wire loose and enables the wire to expand and contract freely with changes in temperature. This configuration reduces long-term stress-induced resistance change, but the downside to this configuration is the susceptibility to vibration. In helix configuration, a bifilar winding is wound around the bobbin and then sealed with some non-conductive coating. This configuration helps protect against vibration, but is prone to long-term stress induced resistance change depending on the RTD element.

Thin-film RTDs are constructed by depositing some metal alloy film onto a substrate, etching the shape of the resistive element, and then sealing the sensor. These types of RTDs are smaller, faster, and much less expensive than wire-wound RTDs. The drawbacks to thin-film RTDs include poor long-term stability and narrower temperature range. However, this style is better for shock and vibration environments. The two RTD styles are shown in Figure 2 below.

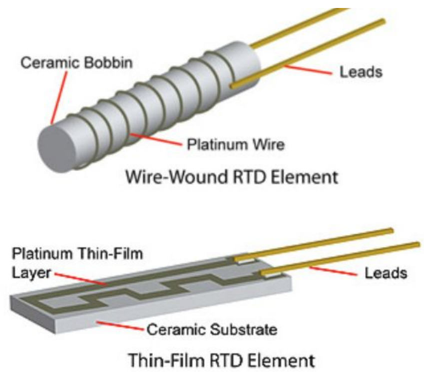

Figure 2: Wire-Wound and Thin-Film RTD Constructions [1]

Overall, RTDs are temperature sensors that are generally used in applications that are in need of accuracy and stability. RTDs can be bulky in size, but provide a wide temperature range depending on the material composition of the RTD. These type of temperature sensors do have an issue of self-heating which will affect the temperature measurements. The best solution to deal with the self-heating is to minimize the length of the wires and to keep the excitation current as low as possible. Higher excitation current generates more heat especially for platinum RTDs.

Implementation

RTDs have three circuit configurations: 2-wire, 3-wire, and 4-wire. 2-wire configuration is the least accurate of the 3 types. In the 2-wire configuration, lead wire resistance is not eliminated from the sensor measurement which results in its measurement error. 3-wire circuit configuration is the choice for industry purposes, where the third wire enables a method for removing the error from 2-wire configuration from sensor measurements. 4-wire configurations is the best option for high-accuracy results while it can also provide the resistance of the lead wires. 2-wire circuit configuration will be implemented since this configuration requires the least amount of supplemental components. The 2-wire configuration is shown below in Figure 3.

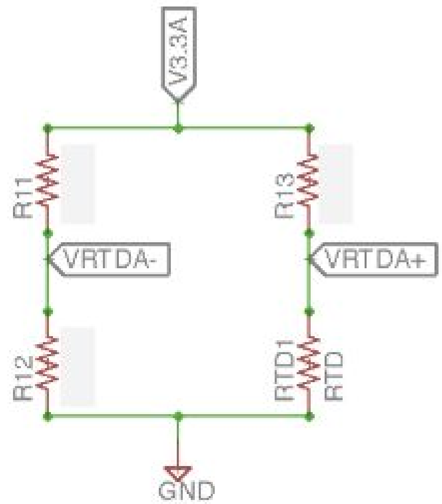

Figure 3: Two-Wire RTD Measurement Circuit

Infrared

Background

Based on the specifications and constraints provided by Hubbell, infrared technology could be utilized in the development of the temperature sensing system. Specifically, the long wave infrared spectrum that encompasses the wavelength of 8 micrometers to 15 micrometers contains the temperature range of -20°C to 80°C. The basis of temperature measurement utilizing the infrared spectrum is the Stefan-Boltzmann Law, which is stated as:

$$P = \varepsilon\sigma A(T - T_c)^4$$

where P is the net power radiated in watts by the target of measurement, ε is the emissivity of the target, σ is Stefan's constant, A is the area of the measurement, T is the temperature of the object being measured in °C, and T_C is the ambient temperature around the object being measured in °C.

Upon inspection of the Stefan-Boltzmann Law, two important aspects of infrared temperature measurement are exposed. The first is that the ambient temperature is needed to measure the absolute temperature of the target. The Stefan-Boltzmann Law shows that the net power radiated is proportional to the temperature of the target relative to the surroundings to the fourth.

The second aspect of infrared temperature measurement seen in the Stefan-Boltzmann Law is that there is an effect on the measurement due to the emissivity of the target. Emissivity is the ratio of power radiated to the power radiated from a black body object. If the object has a high emissivity, the power radiated by that is very similar to that of a black body, and therefore will provide a highly accurate measurement. On the other hand, if the emissivity is very low, the object tends to be highly reflective, and therefore will provide a less accurate temperature measurement of the target.

A major benefit of infrared technology is that it is a non-contact method of measurement. This means the sensor an object can be at a distance from each other. The distance between sensor and object provide protection against damage under extreme temperature conditions.

Many infrared temperature sensing devices are available on the market today including IR thermopiles, the microbolometer, and digipiles. Through the research performed it was found that IR thermopiles are an affordable method of temperature sensing.

IR Thermopile

The typical measurement range of an IR thermopile is -20°C to 100°C with an accuracy of below ±1°C. At a base level, a thermopile is made up of a selected amount of thermocouples. A thermocouple is a junction made up of two dissimilar metals. An example of a thermocouple can be seen in Figure 4 below.

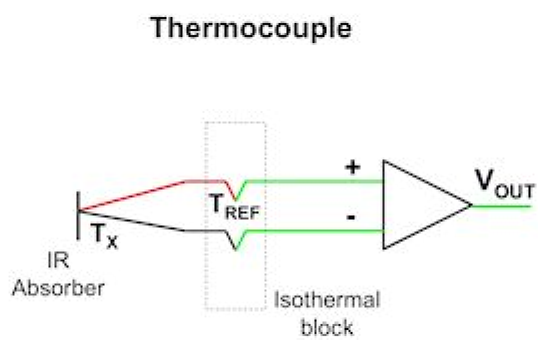

Figure 4: Infrared Thermocouple[2]

When a temperature gradient is across the junction, a small voltage is produced. This is the Seebeck effect. The general equation for the Seebeck effect in a single junction (single thermocouple) is given as:

$$V_{Out} = S * (T - T_{Ref})$$

where V_{out} is in volts, S is the Seebeck coefficient in Volts per degree celsius, T is the temperature at the junction of the dissimilar metals, and T_{Ref} is a reference temperature, typically the ambient temperature around the thermocouple. By placing multiple thermocouples in series, a thermopile is created. An example of a thermopile is shown in Figure 5.

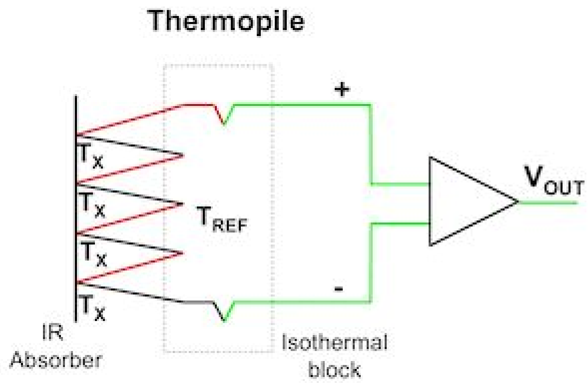

Figure 5: Infrared Thermopile [2]

A thermopile functions under the same principle as a thermocouple, however is represented by the equation:

$$V_{Out} = N * S * (T - T_{Ref})$$

where all values are the same as in the equation for a thermocouple with the addition of N which is the number of thermocouples in the thermopile. A thermopile will have a higher output voltage than a thermocouple, however the value is still in the millivolt range.

As seen in the above equations, IR thermopiles utilize infrared radiation in a different way than other infrared devices. For an IR thermopile, there is an IR absorber layer at one end of the metal junctions. The absorber layer will then produce the temperature difference necessary to produce a voltage correlated with the temperature of the object.

In both the Stefan-Boltzmann Law and the equations describing the Seebeck effect, a reference or ambient temperature must be known. Many existing thermopile packages contain an internal RTD. The resistance of this RTD can be measured to calculate the ambient temperature.

While IR thermopiles have benefits such as the non-contact measurements, there are some issues associated with this technology. The first major issue deals with the material of the object of measurement. If the target has a very low emissivity, it tends to reflect infrared radiation from other object causing inaccurate temperature measurements. This could be fixed by applying tape or paint to the target object, however is impractical in the field. Another issue associated with thermocouples and thermopiles is that of cold junctions. This would mean another dissimilar metal junction is formed that could follow the Seebeck effect. This issue can be compensated by material selection as well as component selection.

Implementation

When utilizing IR thermopile devices, the signal conditioning circuits required are an amplification circuit and a circuit to measure the ambient temperature. For the devices for this purpose, a possible circuit implementation is shown in Figure 6.

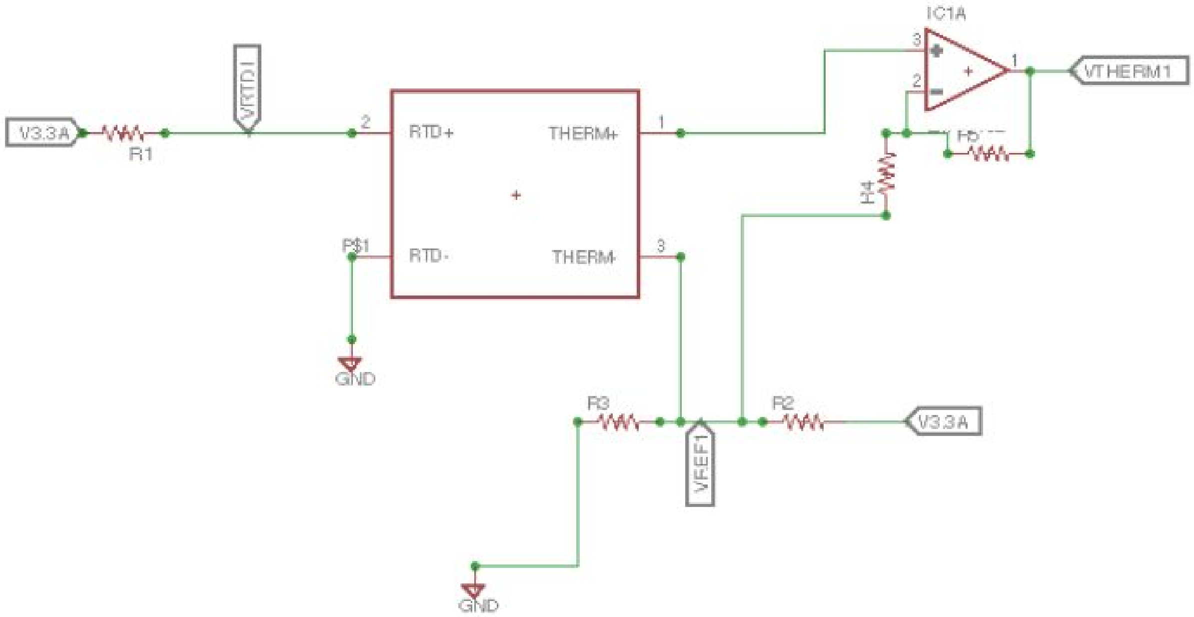

Figure 6: IR Thermopile Circuit Configuration

In the schematic shown in Figure 6, the amplification of the thermopile output is performed by a low noise, rail-to-rail op amp. Utilizing a single supply of 3.3 volts, the thermopile must have a bias applied to compensate for the negative output of the thermopile. The resistance values for the amplifier will change based on the output values of the thermopile. The output voltage of the amplifier circuit is given as :

$$V_{\text{Therm}} = \frac{R_5}{R_4} * V_{Output} + V_{Ref}$$

To measure the ambient temperature, the RTD found in the IR thermopile packages is placed in a voltage divider configuration so the resistance can be determined and used for temperature computations. The resistance of the RTD can be calculated using the equation:

$$R_{RTD} = -\frac{R_1 * V_{3.3V}}{V_{3.3V} - V_{RTD}}$$

Utilizing this resistance, the ambient temperature of the sensor can be found.

With the ambient temperature, output voltage of the thermopile, and a calculated constant, the temperature of the measurement target is given as:

$$T_{obj} = \left(\frac{V_{out}}{K} - T_{Ambient}{}^{4}\right)^{\left(\frac{1}{4}\right)}$$

Using the circuit in Figure 6, an IR thermopile can be used to determine the temperature of an object.

Comparison of RTD and Infrared Technologies

Based off of the research performed, both RTD and IR technology have benefits and drawbacks. In the case of RTDs, these devices are highly accurate and require minimal external circuitry. However, one drawback is that close proximity, if not in contact, is required for temperature measurement leading to possible damage to the sensor or target of measurement. RTDs also have a slow response time, sometimes up to 4 seconds to adjust to the proper resistance. When looking at IR thermopiles, the benefit is that of non-contact measurement. One downside to infrared technology is object with low emissivity reflecting power from other objects leading to inaccurate measurements. Both technologies can benefit from the use of a microcontroller for a faster and more reliable temperature measurement.

Microcontroller

Based on the requirements set by Hubbell, a microcontroller is necessary for data interpretation to provide a temperature for the user. The output voltages of both the RTD and infrared configurations must be put through computations for proper usage. Based on the number of inputs needed to have multiple sensors as well as the desired resolution, the Atmega328p chip was originally selected. The Atmega328p boasted "...32KB ISP flash memory with read-while-write capabilities, 1024B EEPROM, 2KB SRAM, 23 general purpose I/O lines, 32 general purpose working registers, three flexible timer/counters with compare modes, internal and external interrupts, serial programmable USART, a byte-oriented 2-wire serial interface, SPI serial port, a 6-channel 10-bit A/D converter (8-channels in TQFP and QFN/MLF packages), programmable watchdog timer with internal oscillator, and voltage operation range," which has been specified by Microchip Technology Inc[3]. The advantages of this chip over the competition is its numerous I/O lines, varias interfaces and ports, and large memory. The Atmega328p is available as both a standalone chip, in both DIP and surface mount configurations, and on a development board. The standalone chip was intended be used for the final board design. The development board was utilized for testing without the need for external circuits to be built. For testing, the UART communication over USB to a computer was used with a Baud Rate of 9600 to readout temperature values.

After various testing, we replaced the Atmega328p with a PIC16 based microcontroller. This microcontroller was very similar in specifications when compared to the Atmega328p but had five more ADC channels, all boasting 12-bit A/D converters. Four of the five added ADCs ultimately were required for our implementation. UART communication carried over from our previous microcontroller and was used in our final prototype.

Testing

As stated previously, both RTD and infrared technologies are being looked at on an experimental level. The testing stage of the project was used to debug, modify, and improve existing circuitry to minimize inaccuracies and finalize a design for further implementation.

For testing purposes, the Atmega328p was used on the ATMEGA328P-XMINI evaluation board. The auxiliary circuits for both RTD and infrared thermopiles were constructed on a breadboard and the outputs of the circuits were read by the microcontroller and output the measured temperature to the user through a UART interface. Both the RTDs and thermopiles were tested with different materials including aluminum, copper, and brass. All of the temperatures of these materials were measured between the given range of -20°C to 80°C and compared to a known temperature sensing device, a thermocouple. The materials tested were in different degrees of tarnishment including; polished, painted, and oxidized.

Using this testing setup, different devices and packages were compared within both RTD and infrared ranges. Multiple RTD or infrared sensors could be tested simultaneously. Finally, RTD and infrared devices were compared side by side measuring the same object.

After evaluating our outputs, we came to the conclusion that a better microcontroller would improve the accuracy of our temperature readings by a significant margin. Given these findings, we changed our microcontroller from an Atmega328p to a PIC microcontroller. The added accuracy due to the increased number of bits of our ADC allowed us to pinpoint our temperature readings. This microcontroller was not available in a development kit which required use to add a USB UART interface integrated circuit device to our testing board. The other analog circuits were not affected by the change of our microcontroller.

RTD Testing

For RTD devices, the Wheatstone Bridge circuits shown in Figure 7 will be used for the 2-wire configuration testing.

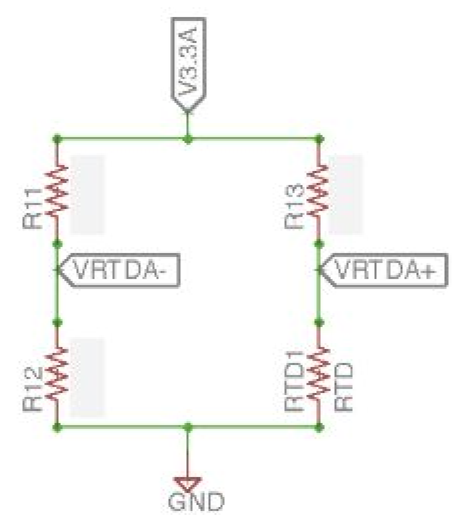

Figure 7: Two-Wire RTD Measurement Circuit

The configuration shown above will require a voltage (V_{Out}) measurement that will be sent to the Atmega328p on an evaluation board.

When looking at the RTD technology, multiple types of RTDs were tested. Both surface mount and through hole components were tested with ranges of nominal resistance values. The resistances of the bridge will vary based off of the nominal resistance of the RTD and therefore the values for testing were not set.

Infrared Testing

Infrared devices, specifically IR thermopiles will be tested utilizing the circuit shown in Figure 8.

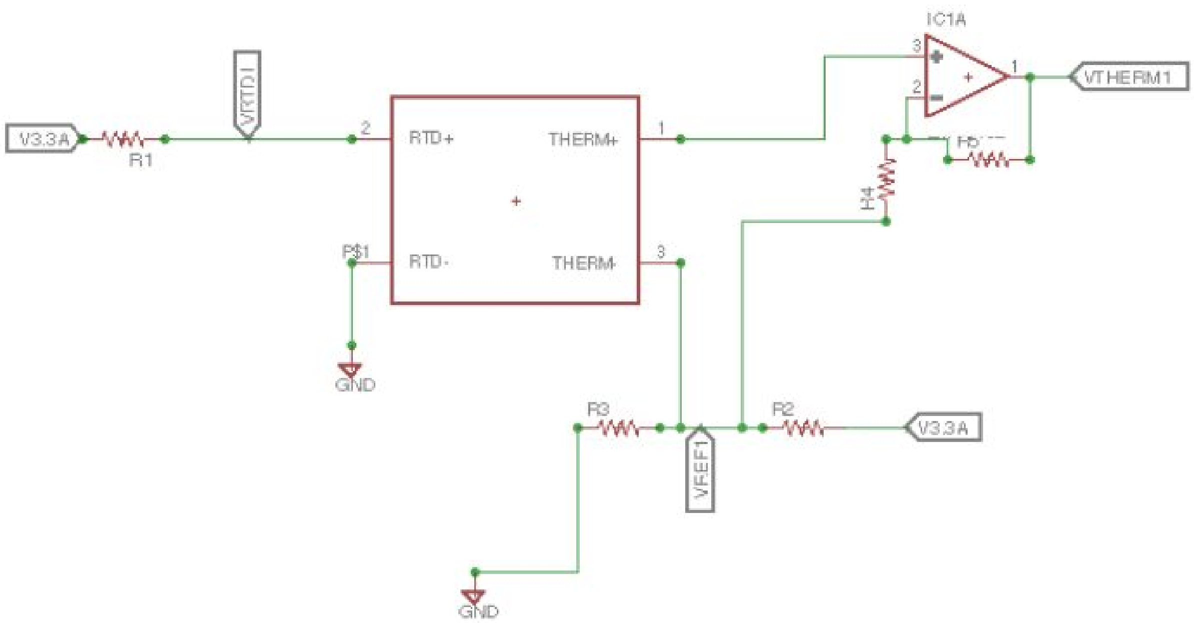

Figure 8: IR Thermopile Circuit Configuration

The amplifier used will be a rail-to-rail type to minimize any saturation and widen the range of input voltages and therefore temperature ranges. The gain of the amplifier was determined based on the output voltage range of the thermopile. The values needed for temperature calculation were read by the Atmega328p on the evaluation board. The calculated temperatures were compared to the known temperatures utilizing a thermocouple.

Prototype

Based on the testing performed, the signal conditioning circuits for both the IR thermopiles and RTDs were finalized. The following circuit implementations were suitable for prototyping.

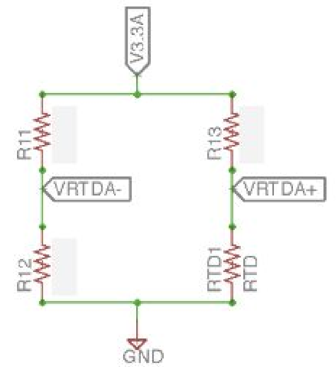

Figure 9: Two-Wire RTD Circuit

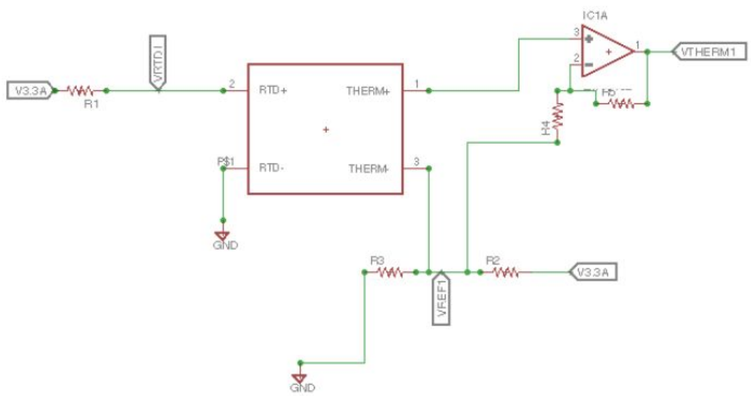

Figure 10: IR Thermopile Circuit

For the PCB prototype, both types of sensors were to be utilized on the board. With this change the ATMEGA328p could not be used as it only has 8 channels of 10-bit ADC. Based on the need for 10 channels of ADC for the microcontroller, a new microcontroller was needed. A new PIC microcontroller made by Microchip was chosen. By utilizing a PIC, the previously used C code for testing could be adjusted to suit the needs of the PCB prototype. The PIC used has 11 channels of 12-bit ADC. The higher resolution ADCs will allow for a more accurate reading of voltage and therefore a more accurate temperature. At the request of Hubbell, we will not be releasing the model of microcontroller chosen.

The prototype was laid out to have two IR thermopiles, two RTDs, signal conditioning circuits, an onboard 8-bit PIC Microcontroller, and any necessary power conditioning circuits. The prototype was to stay within the 1 inch by 1 inch component density. Surface mount components were to be used based on this requirement.

Based on these requirements, the following layout was created in Eagle:

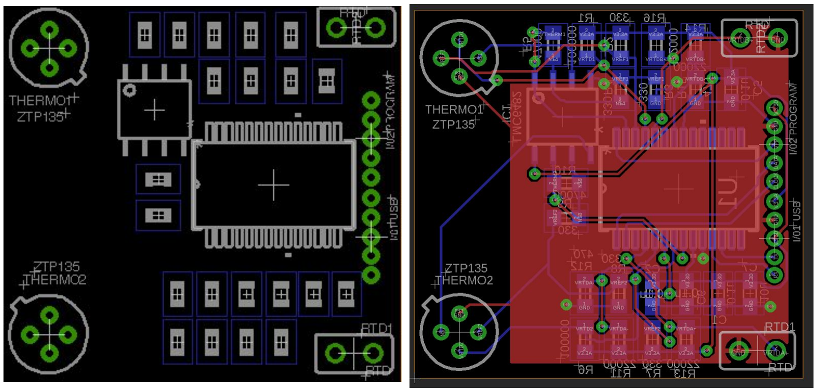

Figure 11: Eagle PCB Layout

Two boards were fabricated, assembled, and the microcontroller programmed. From this, the following boards were used for testing.

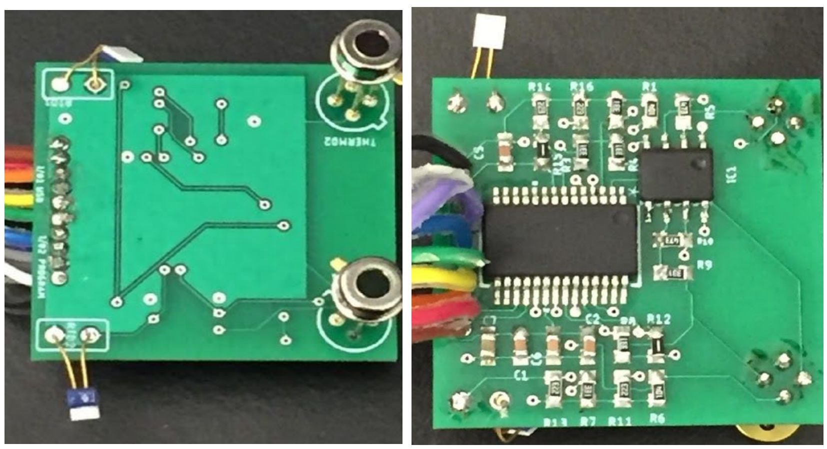

Figure 12: PCB Layout: Physical Board

Code Implementation

The microcontroller performs data interpretation through the use of custom C code. This includes reading ADC values, converting them into corresponding voltages, and using those voltages in application specific calculations in order to receive a temperature readout on our UART connected display. Our code also takes into account calibration variables that are required in order to have accurate readings performed by our sensors. A serial to USB converter is needed to output the values as a terminal readout. Due to the nature of our Non-disclosure agreement no more can be said in regards to the code.

Budget

Hubbell Inc. has not limited the budget for the prototype. It remains flexible, but the ideal budget is still $6 to $8. The tables shown below contain the budget necessary for each sensor design as well as a combined design with the two sensors.

Infrared only design:

	Component	**Quantity Per Board**	**1000 Unit Price**
Sensors	Thermopile	2	2.36205
Resistors	330 Ohm	6	0.04906
	47k Ohm	2	0.04906
	100k Ohm	2	0.04906
Capacitors	0.1uF	4	0.04258
	10uF	1	0.1382
OP AMP	OPAMP	1	0.74526
Microcontroller	16 Bit MicroController	1	1.69950
		Total:	$7.97

RTD only design:

	Component	**Quantity Per Board**	**1000 Unit Price**
Sensors	RTD	2	0.837
Resistors	470 Ohm	2	0.03346
	22k Ohm	4	0.04906
Capacitors	0.1uF	4	0.04258
	10uF	1	0.1382
Microcontroller	16 Bit MicroController	1	1.69950
		Total:	$3.95

Infrared & RTD combined design:

	Component	Quantity Per Board	1000 Unit Price
Sensors	RTD	2	0.837
	Thermopile	2	2.36205
Resistors	330 Ohm	6	0.04906
	470 Ohm	2	0.03346
	47k Ohm	2	0.04906
	100k Ohm	2	0.04906
	22k Ohm	4	0.04906
Capacitors	0.1uF	4	0.04258
	10uF	1	0.1382
OP AMP	OPAMP	1	0.74526
Microcontroller	16 Bit MicroController	1	1.69950
		Total:	$10.46

Conclusion and Future Plans

Our final prototype design was able to meet nearly all requirements of our project. With only the device's cost to produce being over budget, all other design choices were optimal. The implementation of both RTD and infrared technology allowed for the device to accurately read temperatures from any distance and it is able to do so nearly simultaneously between all sensors. All these sensors were able to fit in our 1 inch by 1 inch dimension requirement along with our analog circuitry to support these sensors and the microcontroller. The appropriate pins to program the microcontroller were implemented on the PCB design for use with a PICKit. Given proper calibration and constants for the devices, the design can accurately read measurements given the proper references for the material being measured. It does so by reading the voltages and performing calculations within milliseconds. Overall, our device not only performs properly but also satisfies our design requirements.

Improvements to our design are possible through the optimization of code, minimization of component sizing, and different implementation of supporting circuitry. By adjusting the code on the microcontroller, the measurements can be faster and more accurate. Also, a basic user interface could be added to allow for adjustments to constants, such as emissivity of a substance, for more accurate readings. This would aid in testing purposes.

By outsourcing PCB assembly and soldering, the size of components could be reduced and therefore the overall footprint of the board can be reduced. By selecting higher quality components the accuracy of the design can further be improved. Optimizing the code would also allow for improvements such as self calibration of sensors. Improving a form of displaying output temperatures would be the next logical step in further designing this device. This display in combination with a simple user interface would make this calibration process feasible.

References

[1] http://www.sensortips.com/temperature/designing-with-rtd-temperature-sensors/, Accessed: 22, October 2017

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