

Design of a Heating Chamber for Sensor Characterization

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Abstract

In this project we present a design and fabrication of an economic heating chamber for sensor characterization. The system includes a K-type thermocouple, a MAX31855 thermocouple-to-digital converter, Arduino microcontroller, a 1.2m heater wire, a CMOS power transistor and a 400mL chamber. Thermocouple was placed in the chamber, which can send the temperature value to Arduino by MAX31855 via SPI communication. Arduino microcontroller can act as an on-off controller, deciding if the heater wire begins to heat up the chamber. This is done by making the CMOS transistor turns on or cuts off. A temperature controlling program was made to control the heater.

This project will play an important role for our humidity sensor project. We can set the environment temperature by this chamber and testing the performance of our humidity sensor in different temperature.

The current flowing through the heater wire is 0.8A. It takes about 3 minutes to heat the chamber from room temperature (25 Celsius degree) to 85 Celsius degree.

Introduction

In industrial production process and laboratory research, environment temperatures are needed to be controlled in many cases. For example, researchers use temperature control system to test the performance of their devices in different temperatures. Generally, sensor's performance varies significant different with temperature. [1][2][3][4] The rising temperature can bring heat noise and change the characteristics of the inside transistors of the sensor. [5] These effects could be very harmful, even have a potential to damage the sensor. So it's vital for designers to do temperature characterization for their sensor.

Doing temperature characterization requires temperature control system. However, most commercial temperature controllers in the markets are bulky and expensive, which make them not suitable for sensor characterization. In order to accurately control a chamber's temperature (where we going to put our sensor in) without expensive equipment involvement, we made a controllable heating chamber.

There are three basic types of temperature control system, which are on-off, proportional and PID. [6] An on-off control system is the simplest form. For heating control, the output is on when the temperature below the setpoint, and off above setpoint. Since the temperature crosses the setpoint the change the output state, the process temperature will be cycling

continually, going from below setpoint to above, and back below. We used on-off system as our controlling system.

Basically, temperature control system consists of a temperature sensor, a heater and a feedback loop. In this study, K-type thermocouple was used as our temperature sensor.

Compared with commercial temperature sensor IC, thermocouple has a lot of advantages. Thermocouple provides measurement over a large temperature range. For K-type thermocouple, it can measure a range of temperature from -180 Celsius degree to 1300 Celsius degree. Also, thermocouple has the ability to directly contact with the material they are measuring, which makes it more accurate. [7] However, thermocouple's output voltage is sensitive to the temperature difference between its two junctions (measurement junction and cold junction). Ideally, we hope the temperature of cold junction is 0 Celsius degrees. This can be done by putting the cold junction in ice water. Then the output voltage of thermocouple can directly reflect the temperature of the hot junction.

In real life applications, it's hard to get a zero temperature reference point for the cold junction. So in order to get the temperature of the measurement junction, cold junction compensation must be made to counteract the influence of the cold junction. This can be done by using MAX31855 Cold-Junction Compensation Thermocouple-to-Digital Converter.

The MAX31855 can compensate the cold junction voltage and convert the thermocouple's output from analog to digital and interface with Arduino microcontroller using SPI communication. [8]

We can use our expected temperature as the setpoint of the on-off control system. Arduino will compare the measurement temperature and the setpoint and decide whether to make the heater start working. The heater and the thermocouple form a feedback loop. In this way a temperature control system was created.

Basic theory of thermocouple

A thermocouple is a temperature-measuring device consists of two dissimilar conductors that form two junctions, which are measurement ("hot") junction and reference ("cold") junction. For K-type thermocouple, it is formed by nickel-cadmium and nickel-silicon alloy.

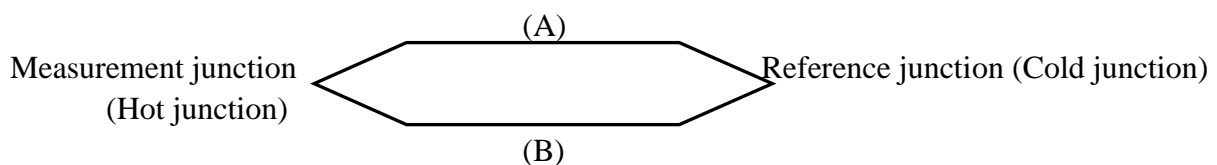


Figure 1: Structure of thermocouple

The output voltage of thermocouple depends on the temperatures of both the measurement junction and the reference junction based on Seebeck effect. If A, B are different metals which form a close loop. The temperature differences between the two junctions will create electrical potential. Since thermocouple is a differential device rather than an absolute temperature measurement device, the reference junction temperature must be

known to get an accurate temperature reading. This process is known as cold junction compensation.

System design

Our system consists of the thermocouple sensing part, the MAX31855 compensating and A/D converting part, and the heater controlling part. The schematic is shown as Figure 2.

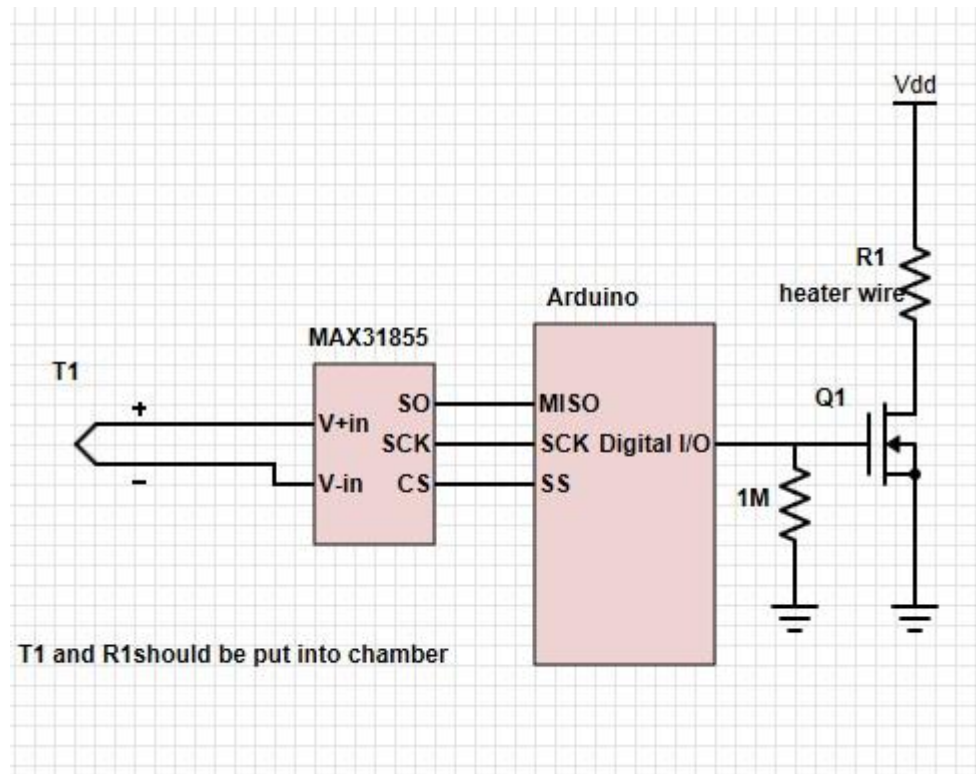


Figure 2: System of the heating chamber (simplified schematic)

It's important to add the 1M ohms resistor to the gate terminal of the power transistor. Power transistor has a very large capacitance between its gate and source terminal. When Arduino output 5 volt to gate, it will charge the large equivalent capacitor between the gate and source terminal. When Arduino begin to output 0 volt, the capacitor will discharge, causing gate's voltage be hold at a high value, which make the transistor keep turning on. Adding a large resistor between the gate-source terminals could increase the discharge speed of the gate-source capacitor to make the transistor cutoff right after Arduino output 0 volt.

In order to get a better circuit performance, we need to build a low-pass filter at the output of the thermocouple. Because the long wire of thermocouple may work as an antenna, which will cause Electromagnetic interferences (EMI). [9]EMI noise signal has a very high frequency, typically over 500 kHz. We can use RC filters for noise reduction.

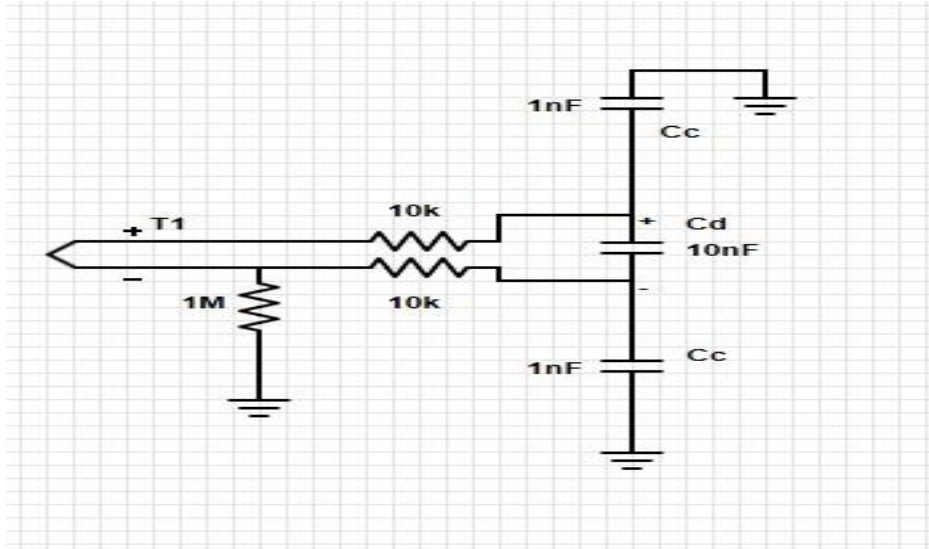


Figure 4: Low-pass filter for thermocouple

Filter cutoff frequency (differential) = $1/(2\pi R(2C_d + C_c)) = 758 \text{ Hz}$

Filter cutoff frequency (common) = $1/(2\pi R C_c) = 15.9 \text{ kHz}$

The two $10\text{k}\Omega$ resistors and the 10nF capacitor form a differential filter with a cutoff frequency of 758 Hz . The two 1nF capacitors form common-mode filters with a cutoff frequency of 15.9 kHz . By adding a RC filter, the EMI can be eliminated.

As we mentioned above, MAX31855 has a temperature compensation design, which can sense and correct the change in the reference junction (Cold junction) temperature. It does this by first measuring its internal die temperature, which should be held at the same temperature as the temperature junction. It then measures the voltage from the thermocouple's output at the reference junction and converts this to the non-compensated thermocouple temperature value. This value is then added to the device's die temperature to calculate the thermocouple's "hot junction" temperature.

MAX31855 also has a built-in 14-bit analog-to-digital converter (ADC), which converts the output of the thermocouple from analog to digital. Then using SPI communication, MAX31855 can send the temperature values to Arduino microcontroller.

One of a digital I/O pin of microcontroller was connected to the gate terminal of a CMOS power transistor. This pin can output 5V or 0V , which makes the transistor turn on or cut off. The heater wires and the DC power were connected to drain terminal of the transistor. So when the transistor turns on, the current will flow through the heater and make it work.

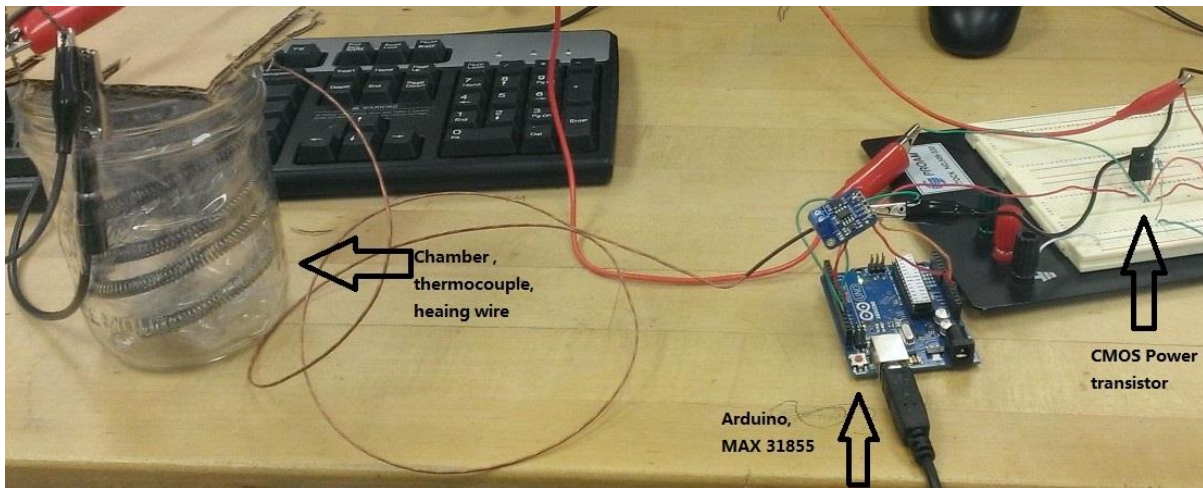


Figure 5: Photograph of the whole system

Software design

A temperature comparing program was designed to control the heater. Arduino IDE provides a serial monitor that allows users to send characters via Serial port. In this project we use this point to set our temperature.

In default, the setting temperature will be zero. When Arduino received temperature values from MAX31855, it would periodically compare the received temperature with the setting temperature. If the received temperature is higher, then the digital I/O pin will be cleared to make the heater stop working. Else the digital I/O pin will be set to 5V to make the heater work. The heater will keep heating the container until the temperature reaches the setting value.

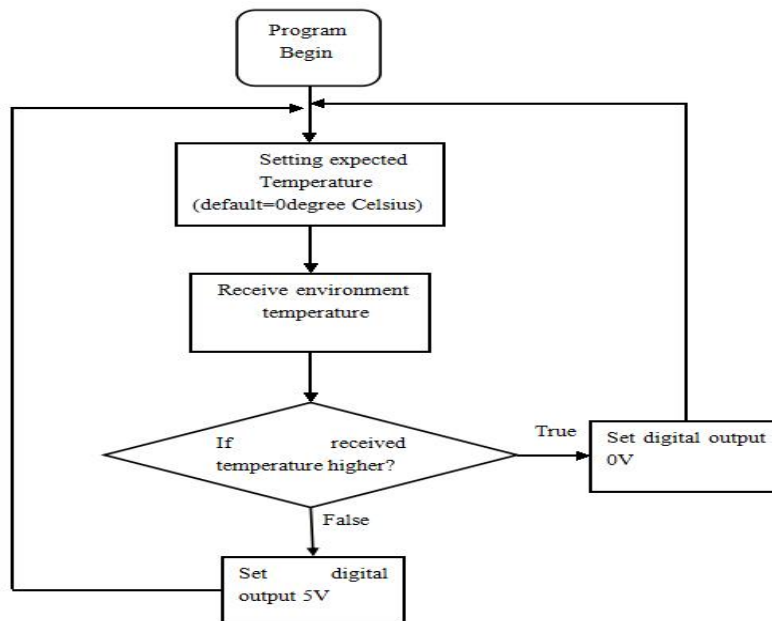


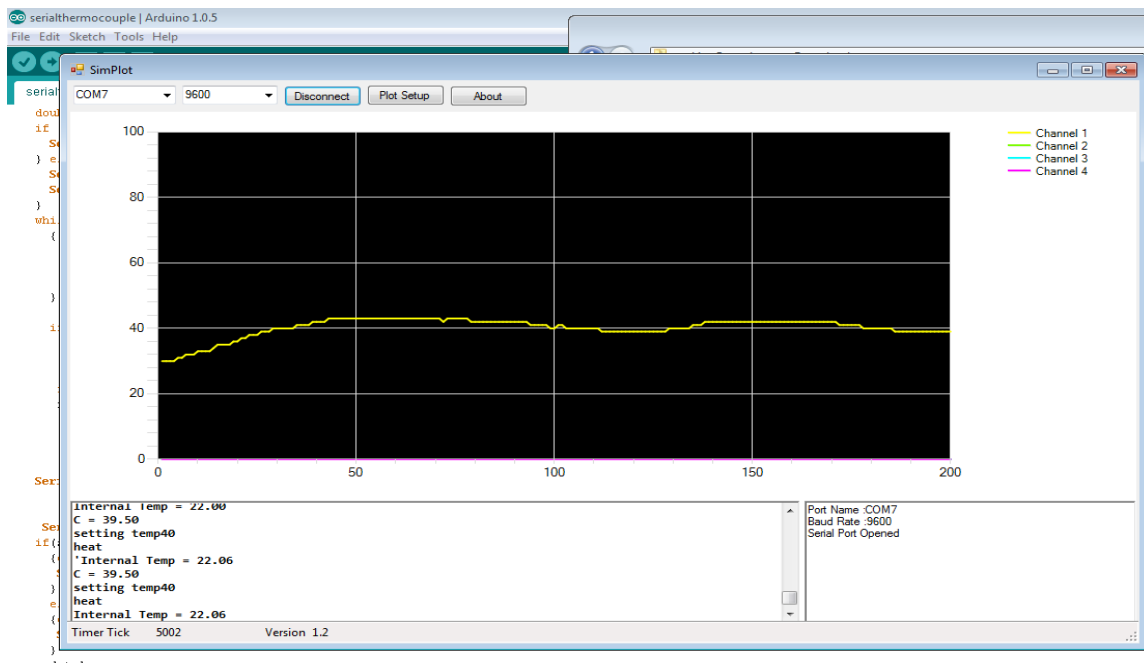
Figure 6: Flowchart of controlling program

Considering Arduino can only receive 1 character each time, an array was created to store the 2-digit temperature value. Also, the character being sent to Arduino was first converted to ASCII number by computer, so we must convert it back to decimal number by Arduino. A temperature setting program was made to do the jobs above.

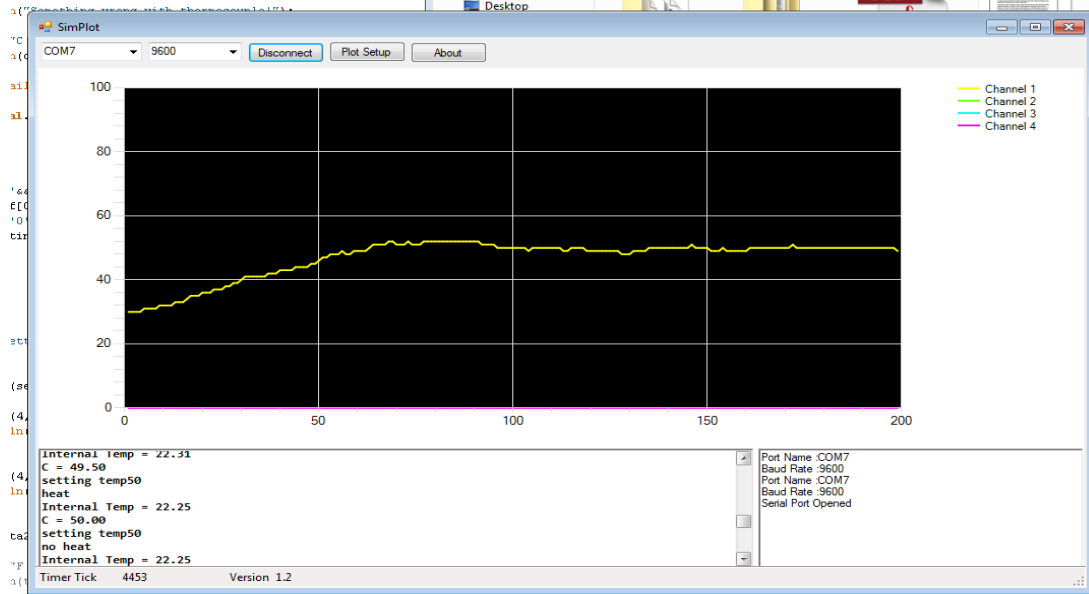
Simplot is a real-time plot software. It can read and plots data from a microcontroller via serial port. In order to use Simplot, we just need to create a data package with a '0xCDAB' header name. Then using Serial.write() function to send the data to Simplot. Typically, doing real time plot requires various scripts of Python. However, using Simplot we just need to write a few lines of code to make it work. Simplot's simple and powerful make it an ideal choice for us to monitor the chamber's temperature.

Result

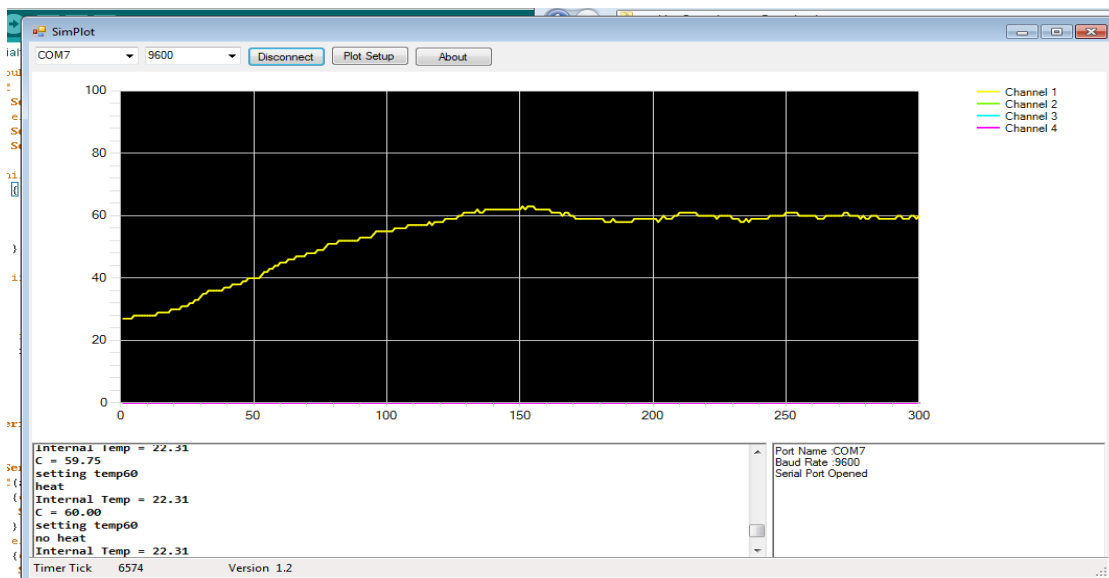
In this study, we tested our heating chamber by setting it to 40, 50, 60 and 70 Celsius degree from room temperature and monitor its performance by Simplot. The results are shown as Figure 7.



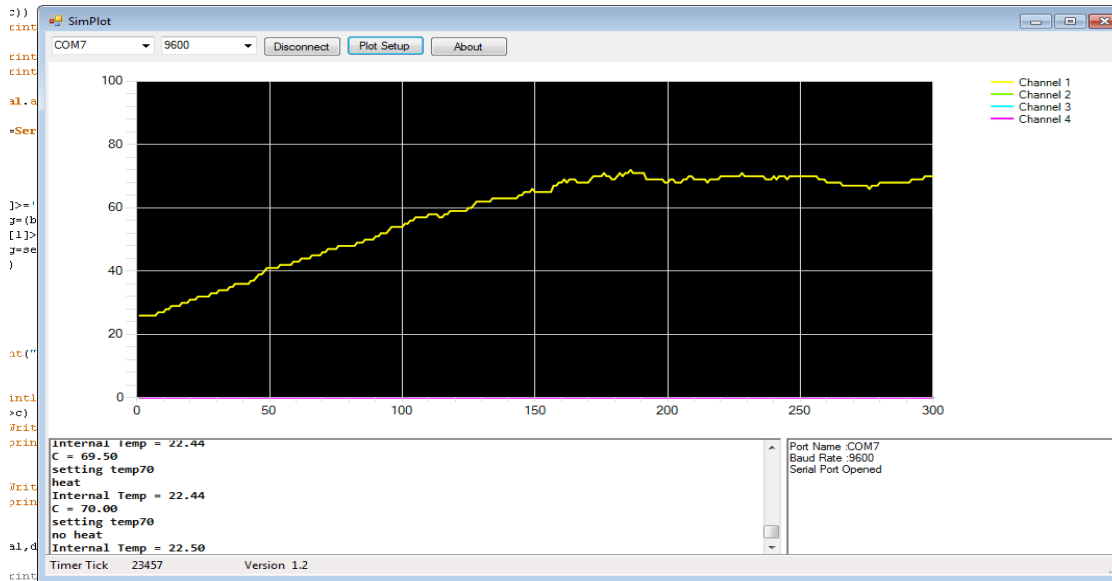
(A)



(B)



(C)



(D)

Figure 7: (A) Chamber’s temperature with a 40 Celsius degree setting value. (B) Chamber’s temperature with a 50 Celsius degree setting value. (C) Chamber’s temperature with a 60 Celsius degree setting value. (D) Chamber’s temperature with a 70 Celsius degree setting value.

Our heating chamber shows a very good performance for its speed and accurate. By passing 0.8A current, the chamber can have an approximately 15.58 Celsius degree/min heating rate. Also, using a traceable control company’s digital thermometer, we measured the actual temperature value of the chamber when Simplot shows the temperature is stable. The results are listed in Table 1.

Setting temperature	Actual temperature	Error rate
40 Celsius degree	41.8 Celsius degree	4.5%
50 Celsius degree	53.2 Celsius degree	6.4%
60 Celsius degree	61.2 Celsius degree	2.0%
70 Celsius degree	70.3 Celsius degree	0.4%

Table 1: Comparison of actual and setting temperature of the chamber

Conclusion

We designed, prototyped and tested an economic heating chamber by using a thermocouple-heater feedback loop. The system contains a K-type thermocouple and a

MAX31855 thermocouple-to-digital converter that is able to collect the temperature values from the environment and send it to the microcontroller via SPI interface. The microcontroller can be used to set expected temperature, which will be compared with the environment temperature. According to the comparison result, a digital I/O pin will be set to 5V or 0V to control the current flow through the heater wires by a CMOS power transistor. The economical, simple design of our system makes it a promising choice for laboratory research activities.

This project was aimed to provide a testing environment for our novel humidity sensor, which will play an important role in that project. We hope to test the performance of our humidity sensor in different temperatures. This temperature control system can be used to set the environment temperature value for that project. After finishing this temperature control system, several tests will be performed using this system to evaluate our humidity sensor.

Relevance with engineering education

Doing this project is a good research experience. It provides us a deeper understanding about how to solve real-life problems which are very different from those works in courses. The knowledge of microelectronics, microcontroller and digital circuit are used in this design. By doing this research, we also learned the engineering development process like problem defining, planning, designing, making it a prototype and testing. This project benefits us greatly in other researches and our academic careers.

Bibliography

- [1] M. Hudspeth and T. Kaya, "Collagen as Dielectric Humidity Sensing Material," Material Research Society Spring Meeting, San Francisco, CA, April 2012.

- [2] T. Kaya, H. Koser, and E. Culurciello, "A Low-Voltage Temperature Sensor for Micro Power Harvesters in Silicon-on-Sapphire CMOS," *Electronics Letters*, 42, 526-528, 2006

- [3] S. Shapardanis, M. Hudspeth, and T. Kaya, "Design and Implementation of Collagen-Based Capacitive Relative Humidity Sensors," IEEE Sensors, Baltimore MD, November 2013.

- [4] Matthew Duff, Joseph Towey, "Two Ways to Measure Temperature Using Thermocouples Feature Simplicity, Accuracy, and Flexibility," *Analog Dialogue* 44-10, October 2010.

- [5] Maxim, "MAX31855 Cold-Junction Compensation Thermocouple-to-Digital Converter," [Online]. Available: <http://www.maximintegrated.com/datasheet/index.mvp/id/7273/t/do>.

- [6] B. Razavi, "Fundamentals of Microelectronics 2nd edition". John Wiley & Sons, Inc. 2008 ISBN 978-0-471-47846-1.

[7] OMEGA, “Introduction to Temperature Controllers,” [Online]. Available: <http://www.omega.com/prodinfo/temperaturecontrollers.html>

[8]S. Sherbrook and T. Kaya, “Development of a Physiological Activity Monitoring Platform,” American Society for Engineering Education (ASEE) North Central Section Conference, 2012.

[9] Dooley, Laurence S and Evans, W. Alun (1986). ”Thermocouple and RTD approximations for the design of portable microprocessor-based simulators” *Transactions of the Institute of Measurement and Control*, 8(5) pp. 235–240.