PELTIER TEMPERATURE CONTROLLER

A Design Project Report

Presented to the School of Electrical and Computer Engineering of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

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Submitted By

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Abstract

Master of Engineering Program

School of Electrical and Computer Engineering

Cornell University

Design Project Report

Project Title: **Peltier Temperature Controller**

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Abstract: This project is designed to build a controller to control the bath temperature of a petri dish. The device will be used by student lab of neurobiology to conducting experiments on fruit flies' thermo channels. An ideal device should have the following feature: easy to use, small development budget (less than $100) and satisfying the performance requirement for conducting experiments. The project is based on an atmega-1284 microcontroller as the main control unit with a PID control algorithm running inside. The petri dish's bath temperature is heated or cooled by a Peltier Plate. A Thermistor is used as the temperature detection device and sent feedback to the microcontroller regarding to current bath temperature of the petri dish. All components are connected with analog circuits to form a close loop feedback controller in order to dynamically control the petri dish's bath temperature. Graphic user interface is built with MATLAB to provide easy user access and monitoring.

Executive Summary

This Master of Electrical and Computer Engineering project is designed to control the bath temperature of a petri dish through a microcontroller-based system. It provides a way for students in neurobiology lab to conduct experiments on a temperature sensitive channel of fruit flies. This system should have an easy-to-use graphical user interface (GUI) so that students can use it easily with a simple user manual. It is also required to have a development budget under $100.

The design and implementation of the project has completed and the first version of the device is ready to use. The device has an average rising time of 5s/℃ and settles within 10s. Tests shows it works stable and accurate among the range of 15 ~ 35 ℃ which satisfies the requirement. The total cost is less than 100$ and with a simple user manual students can easily use it to conduct related lab experiments.

The final product contains two parts: a control unit and an execution unit. The control unit packages all the circuits as well as the microcontroller into a project box. The execution unit is a peltier-thermistor based platform where the petri dish should be put. The complexity and detail of both units are hidden from the user. Separating the two units also largely reduce the negative influence the control circuits may have on electronic noise. To use the device, user only need to follow the user manual to connect two units together and plug in the power supply. In order to make the device more user friendly, a GUI is implemented using MATLAB. The interface is very easy to understand and use. User only needs to type the desired temperature into the GUI interface. The value will then be passed to the microcontroller by serial communication. The interface also contains a dynamic plot to allow the user to monitor the trend of the temperature.

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1. Introduction

1.1 Background and Motivation

Fruit flies (Drosophila) can be engineered to have thermo sensitive channels, which are useful for turning off and on function in biological experiments. One of these channels to be considered as a promising new tool is called Drosophila Transient Receptor Potential channel (dTRPA1). This is a temperature and voltage-gated cation channel that regulates drosophila behavior related to different temperature environment. Previous work has shown that neurons expressing dTRPA1 begin firing action potentials when ambient temperatures rise above 25°C. By delivering modest heat pulses, sets of neurons can be remotely activated in freely behaving animals.[4]

To observe and analyze the neurons' response to the heat stimulus, students who conduct this experiment need a device which can give heat pulse to drosophila. A simple way to achieve this goal is to give a random voltage to a peltier plate so that heat is generated to increase the bath temperature of the petri dish. However, this "open-loop" method has an obvious problem that the heat pulse cannot be controlled. In other words, people can only give a positive or negative voltage to the peltier plate to either increase or decrease its surface temperature, however, the detailed amount of degrees the bath temperature will be changed is not controllable. To conduct experiments more accurately and controllable, a feedback temperature controller is needed.

1.2 Problem Statement & Constrains

There are devices on the market which satisfied the lab requirement mentioned in the last section. However, these devices have two problems. First, the price of the existing device is expensive. Most of them cost more than one thousand dollars. Second, the way to use the device is complicated because the device may have other functions that are fancy but redundant. As a result, a ideal device should be inexpensive and easy to use. With the help of a simple user manual, students conducting the experiment don't have to bother too much on learning how to use the device.

Despite constrains on cost and complexity, the low-noise environment is required in the lab so that PWM is unacceptable. Furthermore, in order to eliminate the electronic noise, the control circuits (power supply, DAC, power amplifier, etc.) have to be completely separated and keep distance from the petri dish. Based on these constrains, the section 1.5 lists the design specification for this project required by students lab of neurobiology.

1.3 Range of Solutions

Previous work has been done to attempt to build a temperature controller. An in expensive way is proposed by Correges P, Bugnard E, Millerin C, Masiero A, Andrivet JP, Bloc A, Dunant Y[1] mentioned the usage of peltier plate but since no control cirtuit was used, the precision was low. But the idea of using peltier plate as an inexpensive way of generating heat is adopt in this project design. Other works tried with electronic device or circuits but either had a relatively higher cost or may lack an easy way to use the device (GUI, LCD monitor, etc.). [2][3][5][6]

The range of solutions can be divided into two categories, pure analog circuit design and microcontroller-based design.

It is possible to build a pure analog circuit function as a temperature control unit. The advantage of this design is a quick speed execution. However, since a GUI interface is required, this solution is not the best for this project design problem. On the other hand, microcontroller-based design provides a serial communication that can be used to build a GUI interface on any computer. With a proper algorithm implemented, the response speed of the microcontroller is fast enough to satisfy the specification. The next section gives an overview of the scheme to design this project. Design detail of each Unit is discussed in section 2.

1.4 Project Design Overview

The system can be divided into three parts, which are temperature detection unit, temperature control unit and GUI user interface. In order to detect the current bath temperature, a thermistor along with a voltage divider circuit is used. When sensing the different temperature, thermistor will have different resistance which is reflected as a different voltage drop in the voltage divider circuit. By continuously taking ADC samples from this voltage, the microcontroller can get the information about the current bath temperature of the petri dish.

For the temperature control unit, the main components include an atmega-1284 microcontroller with a PID control implemented, difference amplifier circuit, digital to analog (DAC) circuit and a power amplifier circuit. The microcontroller outputs control signals based on the desired temperature it get from user and the current temperature detected by the thermistor. The DAC and difference amplifier is used to convert the eight bits output from microcontroller to an analog signal ranging from -12V to +12V. The control signal is then output through a power amplifier to drive the peltier device to either increase or decrease the bath temperature of the petri dish.

For the GUI interface, MATLAB is chosen as a foundation. The interface is designed to be easy to understand and use. To use the device, user only need to type the desired temperature into the GUI interface. The value will then be passed to the microcontroller by serial communication using USB. The interface also contains a dynamic plot to allow the user to monitor the trend of the current bath temperature in petri dish.

1.5 Design Specification

The following is the design specification, note that it’s not the final result of the product but a minimum requirement to ensure the product can be used for related experiments.

- Cost: less than 100$
- Rising time: 12s /℃ (settled within 10 s)
- Temperature range: 20 ~ 30 ℃
- Design requirement: low noise, low cost, easy to use

2. System Design

2.1 High-level Design

Figure 1 illustrates the overview of the project design. As the diagram shows, the device can be divided into three parts: temperature control unit, temperature detection unit, and GUI interface. The temperature detection unit keeps detecting the current bath temperature of the petri dish and sending it back to microcontroller. The control unit starts from running the PID control algorithm inside the microcontroller based on the current temperature detected by thermistor and the desired temperature input by the user through the GUI interface. The output from the microcontroller went through the digital to analog converter, a difference amplifier and then a power amplifier. The signal after the power amplifier will have enough power to drive the peltier plate to distribute or absorb heat on its surface.

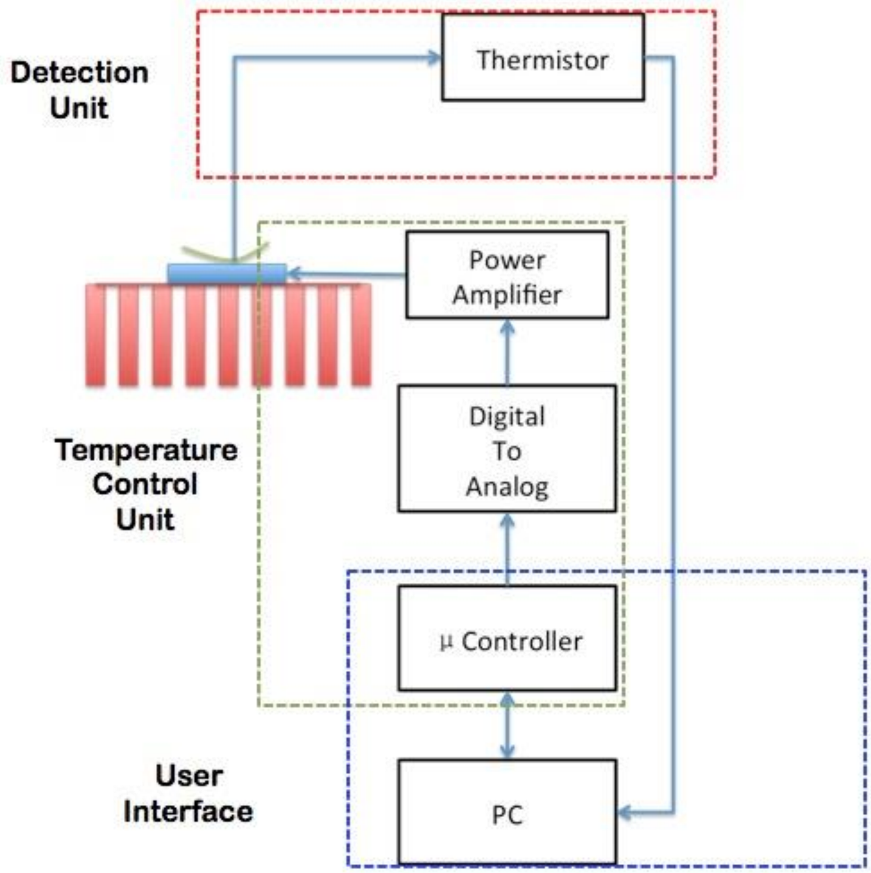


Figure 1. Overview of the Project

2.2 Control Unit Design

2.2.1 PID Controller

The control unit starts when the microcontroller receives the desired temperature from user. There is a PID control algorithm implemented inside the microcontroller which output the control signal based on the current temperature detected from thermistor and the desired temperature. Considered as one of the best and common use controller in industrial control systems, PID controller can provide control action design for specific process requirement by tuning the three parameters. The three parameters are the proportional (P), the integral (I), and derivative (p) values. P depends on current error, I on the accumulation of past errors, and D keep track on the trends of future errors. The weighted sum of these three values provides the control signal to the peltier plate. Figure 2 illustrate the flow chart of a typical PID controller.

The value of P, I, D was calibrated by the required specification of the device (listed in section 1.5). The rising time should be less than 12 second per 1 Celsius degrees rising from 20 to 30℃. The temperature should be settled within 10 seconds after reaching the desired temperature. Under this requirement, the way to get the P, I, and D is to start from calibrating the proportional gain and left other two zero. After a proper P is set so that the rising time is satisfied for the requirement, D is than modified to smooth the overshooting. By setting a proper P and D, the controller is smooth enough but with a steady state error around 3 Celsius degree. Then Integral gain is modified to eliminate the steady state error.

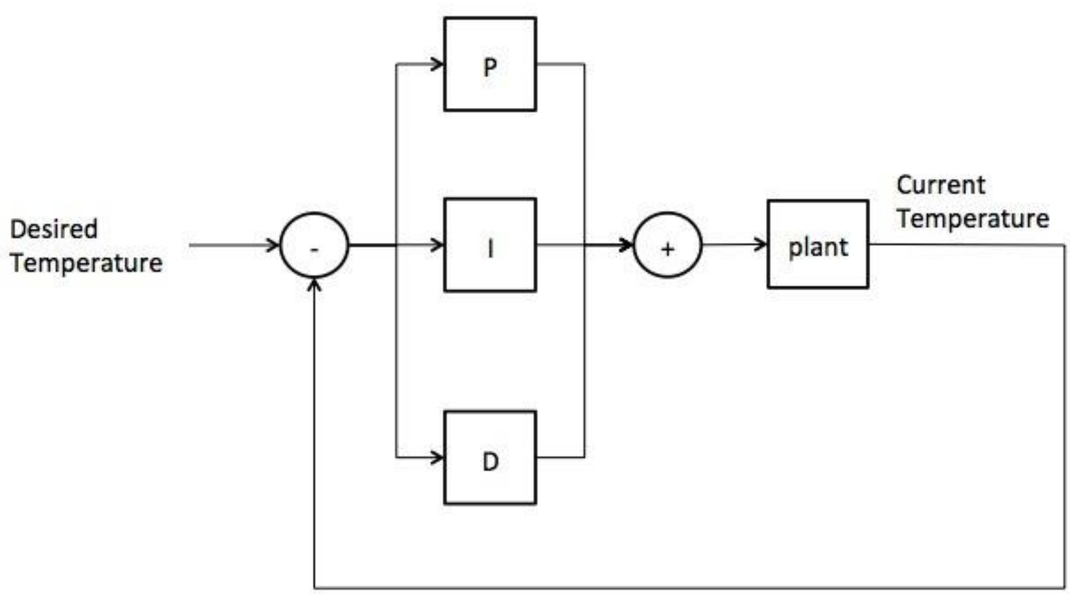


Figure 2. PID Controller Flow Chart

2.2.2 Peltier Plate

This section briefly introduces the principle of a typical modern peltier plate. A peltier plate is based on the thermoelectric effect. A typical thermoelectric device works one of two ways as follow: It creates voltage when there is a different temperature on each side of the device, or conversely, it creates a temperature difference on each side of the device when a voltage is applied to it. Peltier plate is known for the second way described above. Specifically, in figure 3, when the voltage difference is positive between wire a and b, surface A will generate heat while surface B will absorb heat. However, when a negative voltage appears between wire a and b, then the opposite effect occurs. With its quick response, and an inexpensive price on market, peltier plate serves as a good component for this temperature controller design.

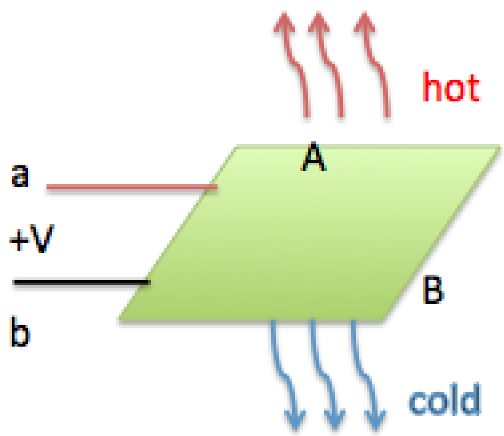


Figure 3. Peltier Plate Working Demo

2.2.3 Control Circuits

Because of the output current limitation of the microcontroller, the control signal coming out from microcontroller has to be amplified and shifted to drive the peltier plate. The ideal result is that the driving voltage of the peltier plate has a range -12V ~ +12V. In order to reach this goal, a circuit schematic shows in figure 4 is designed. This circuit is composed with three main parts: A digital to analog converter (DAC), A difference amplifier and a power amplifier.

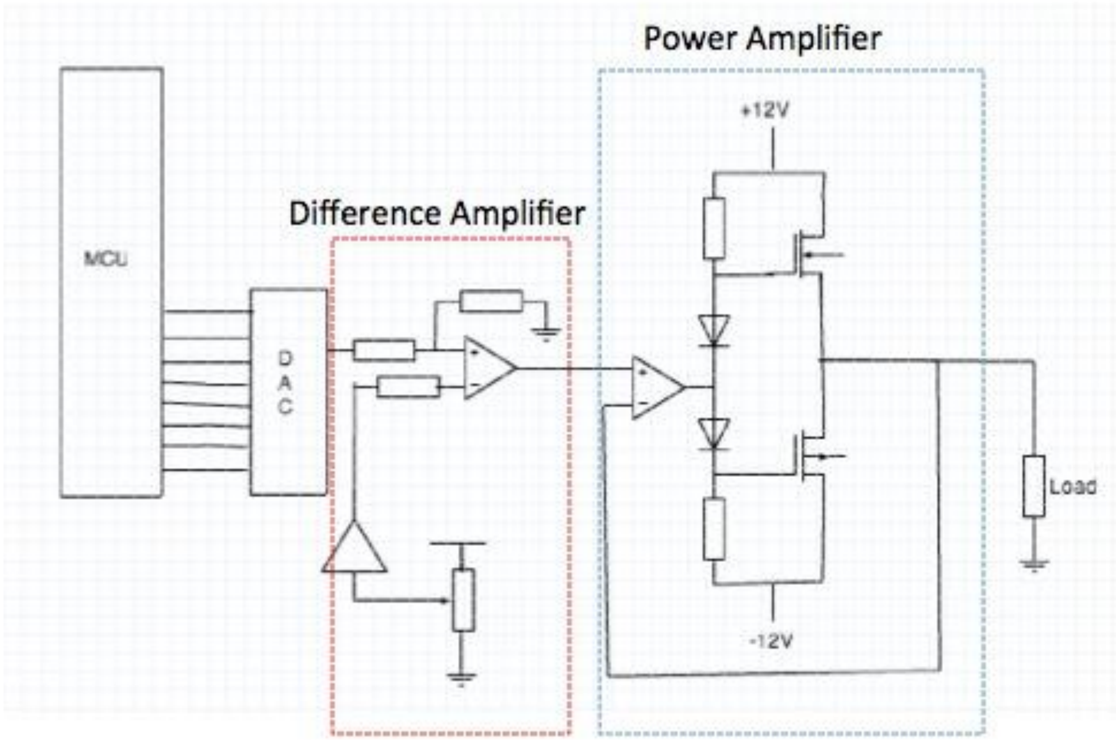


Figure 4. Control Circuit

The DAC is a 4114R-2-RC which can convert an eight-bit digital input to an analog output. A 5 volts from output pin is a logic "1" and a 0 volts corresponds to a logic "0". The combination of the eight output pins from microcontroller forms a range from 0 to 3.2 V at DAC's output.

Because the peltier plate requires a switching of the voltage's direction to either absorb or distribute the heat, the control signal has to be shifted to generate a "negative" voltage. Moreover, the voltage has to be amplified to achieve the full swing of the peltier plate. (-12V~+12V) To achieve this result, a difference amplifier is added into the circuit. The buffer before the negative input is to separate the voltage divider from the rest circuits so that the voltage of the negative input can be decided only by the voltage divider. After the difference amplifier, the output range is shifted and amplified to -12V ~ +12V.

Since the peltier plate has a power consumption of 60W, which means a 5A current under 12 volts drive, a power amplifier is needed to drive the peltier plate. The circuit is built as shown in figure 4. In ideal situation, the output of the power amplifier should has a range of -12V ~12V. However, because of the voltage drop caused by the CMOS transistor, the actual output has a range of -6V ~ 6 V. Unfortunately, the performance is downgraded by half compared to the original design. However, in section 4 the test result will prove that this output range is large enough (Actually the final output is -4.5V ~+6V limited by the over heating problem of PMOS). By tuning the PID parameters, the output control signal satisfied the system requirement. More detail result is showed in section 4.

2.3 Temperature Detection Unit

The Temperature Detection Circuit is illustrated in figure 5. It is a voltage divider with a thermistor inserted as a variable resistor. As the thermistor I used is a NTC thermistor, its resistance would decrease as the increasing of the temperature. The disadvantage of using a thermistor is that its resistance changing is non-linear, which makes it hard to convert back to its corresponding temperature after ADC sampled by microcontroller. Because the range of the temperature is not large, I first tried to use a look up table inside the microcontroller. This scheme worked but the problem is that the look up table is based on the datasheet of the thermistor, which is unfortunately not very accurate. Furthermore, the error is not regular which means it is hard to compensate it in software. To get a better look up table I have to measure every 0.1 degree changing for the thermistor which is not doable. The final solution I took is to sample enough data for the temperate and its corresponding thermistor's resistance, and using MATLAB to find a best-fit function. The function I chose is demonstrated in figure 6. By doing so, the error is within 0.5℃, which is acceptable for this project.

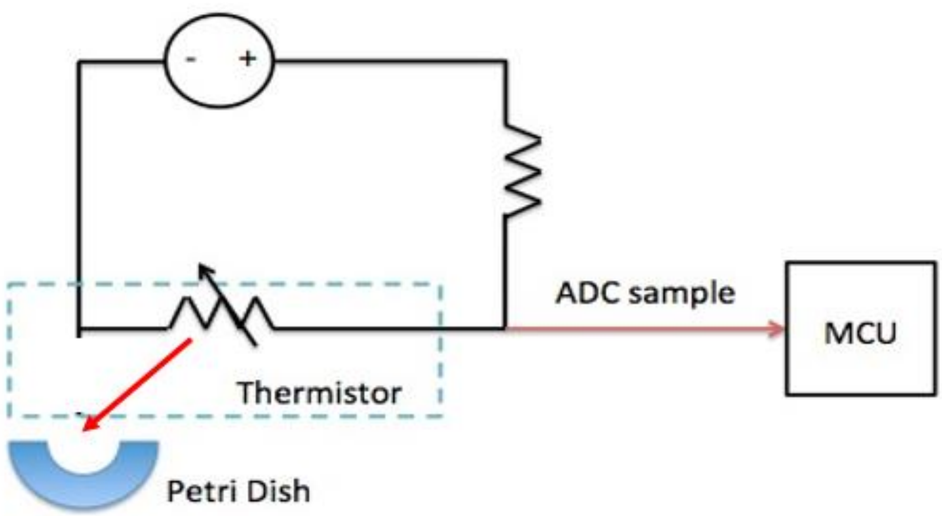


Figure 5. Temperature Detection Unit

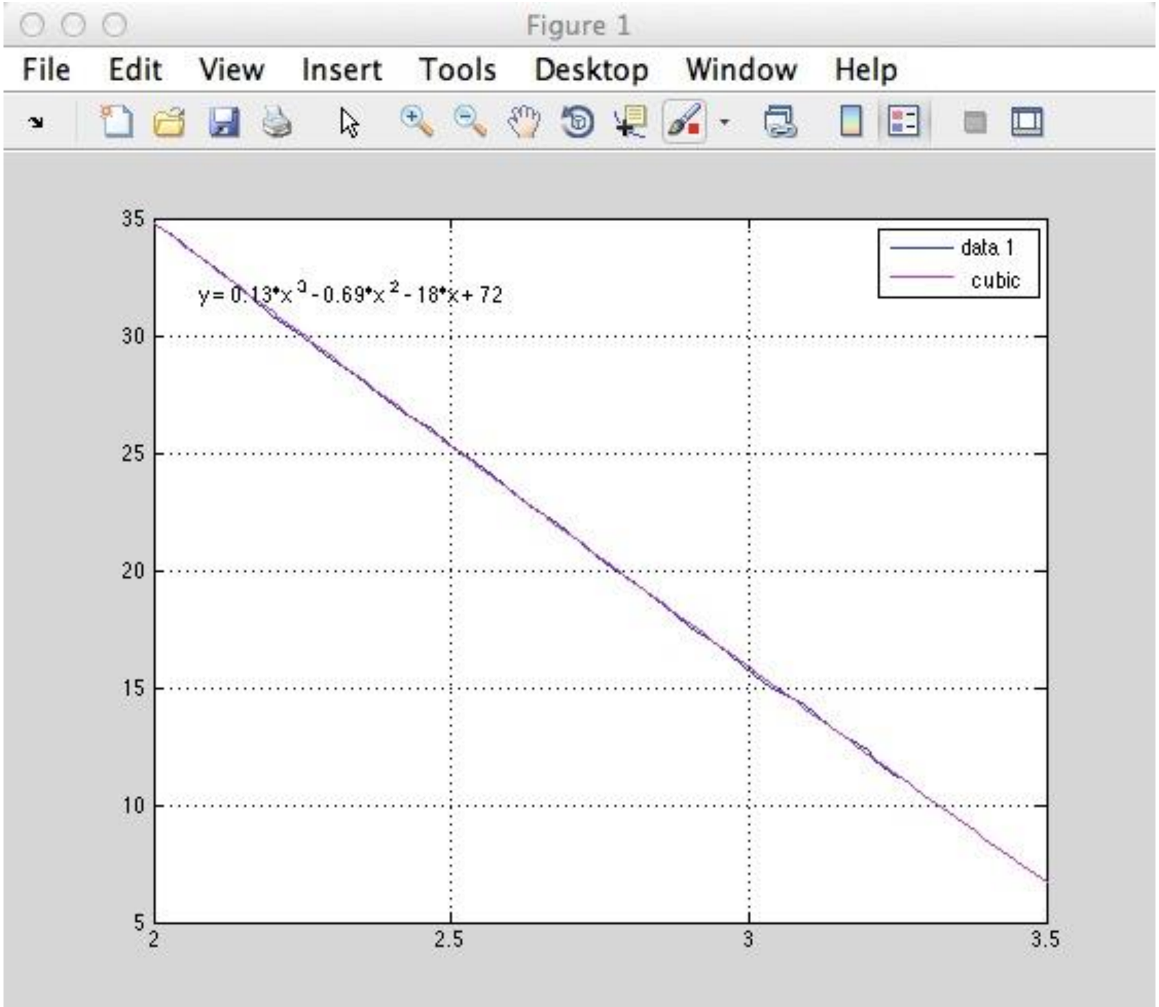


Figure 6. Using MATLAB to Find A Best-fit Function for the Thermistor

2.4 Graphical User Interface

The user interface designed for this project is MATLAB based. The interface is illustrated in figure 7. Since one of the important requirement for UI is easy-to-use. I try to simplify the functional buttons' arrangement on it and make it as simple as possible. The only thing maybe confused is the text window at the bottom-right corner. The use of that is to set the communication port for a serial communication between MATLAB and microcontroller. The communication rate is 9600 baud. The MATLAB function fprint and fscanf does a good job on communicating with microcontroller. By pressing the "detect" button, the ADC sample from the temperature detection unit is passed from microcontroller to MATLAB, which then converted to current bath temperature and is shown in the middle text window. After input the desired temperature in the bottom left text box and pressing the "start" button, the desired bath temperature is passed back to microcontroller. The control unit starts to control the bath temperature. The temperature changing will continually show in current temperature text window as well as in the dynamic plot. By pressing the "stop" button, the device stop to function and ready for new command. The detail MATLAB code can be found in Appendix D.

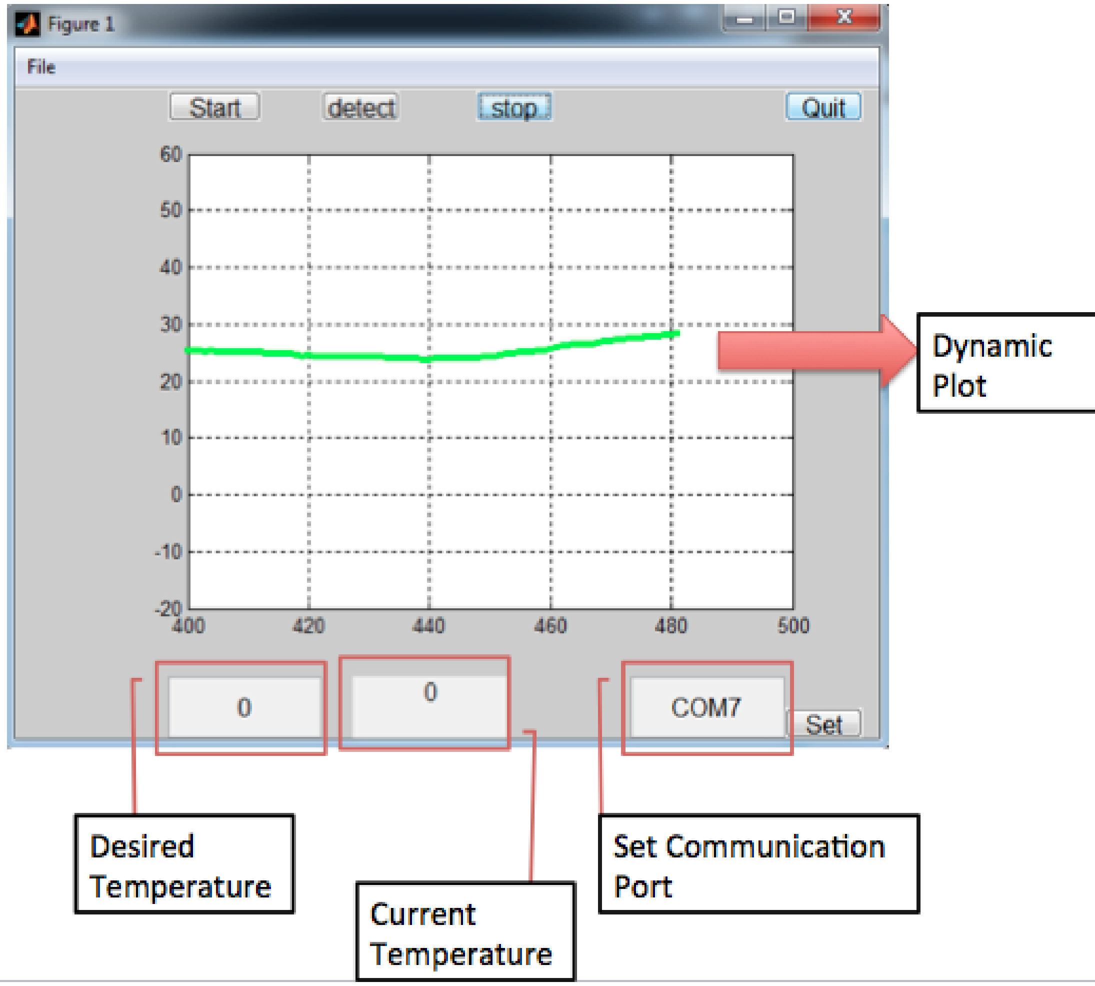


Figure 7. User Interface

2.5 Microcontroller Pin Assignment

The atmel mega 1284 used in this project is developed and used on the development board used for Cornell ECE4760 course. The detail of this hardware can be found in the course webpage: http://people.ece.cornell.edu/land/courses/ece4760/ . To illustrate the pin assignment on the development board, figure 8 is demoed as a simplified version of the development board. It includes all the pins on the board but the location maybe different.

PC0~7 is used for output the control signal. Thus they are connected to the DAC. PA0 is the default port for ADC sampling, it is connected to the thermistor. VCC and Gnd are also connected to the temperature detection unit to finish the voltage divider. An LED is connected to PD0 to indicate the system is on.

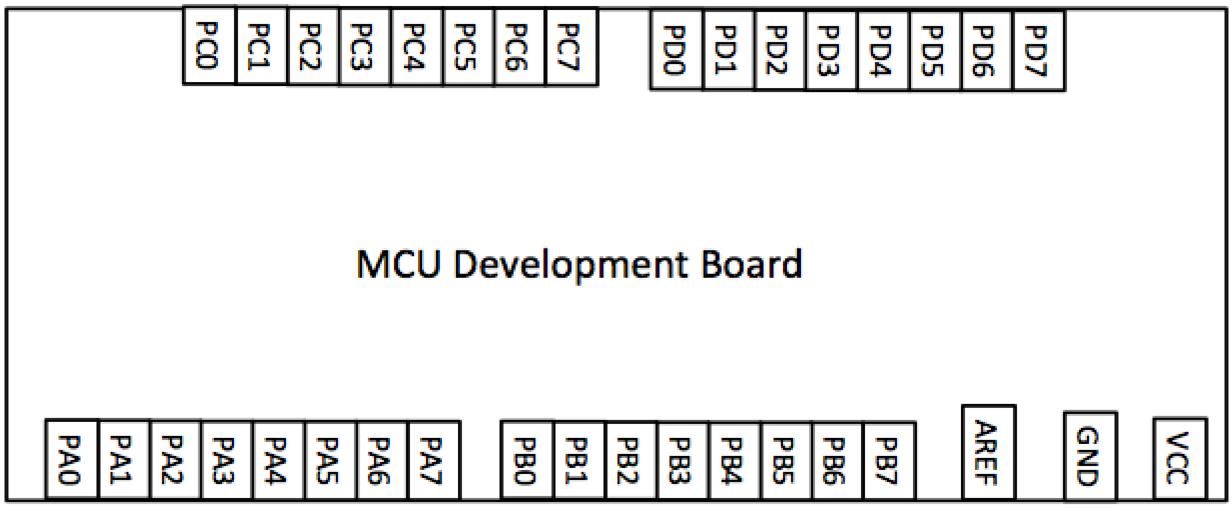


Figure 8. Microcontroller Development Board

2.6 Combine Together

The following process shows the common steps after the system's power is on. Note it also reflects the basic coding process on microcontroller since the whole process is controlled by it. A detailed source code of microcontroller can be found in Appendix C.

Step 1: Power on, LED turned on indicating the system is running. An initial static control signal is output from microcontroller result in a 0V control voltage on peltier plate.

Step 2: Current temperature is detected by the temperature detection unit and passed to microcontroller.

Step 3: A desired temperature is input, and passed to the microcontroller.

Step 4: PID algorithm is running based on the error between current temperature and desired temperature. A dynamic control signal is output to drive the peltier plate. This step is continually repeated until a "stop" signal is sent from user.

Step 5: Get the "stop" signal, stop the current process and go back to step 1.

3. Implementation and Packaging

3.1 Project Box

In order to separate the control circuits away from the petri dish, all the control circuits are put separately in a project box including the microcontroller. Since the CMOS generate large amount of heat when the system is running, heat sink is required for both NMOS and PMOS. The initial implementation used the small heat sink which can be attached to the CMOS so that they don't need to be taken off from the circuit board. However, tests show that these small heat sinks cannot efficiently distribute the heat away. As a result, big heat sink has to be used and CMOS has to be moved off the circuit which increase the size of the device. One optimization to decrease the device size is to build the circuit board in three dimensions. Instead of building all circuits on one board, circuits are divided into three portions and put on three boards. These circuit boards are then connected together vertically. This "three-folded sandwich" scheme effectively saves 1/3 of circuits' size horizontally and thus decreases the size requirement for the project box. Same scheme is also used to put one power supply above another.

There are four different types of the connecters on the project box. A USB port is used to connect to PC for serial communication between microcontroller and GUI. Two banana sockets are used connect to the peltier plate so that the control signal can be passed from control unit to the peltier plate. Another two banana sockets are used to connect thermistor of the temperature detection unit described in section 2.3. Finally a power plug is used to connect to the power supply. The inside structure of the project is shown in figure 9. Note that there is space saved for further improvement such as adding a fan to distribute the heat. The size of project box is 14.17×7.87×5.91 inches. Pictures of the project box can be found in Appendix A.

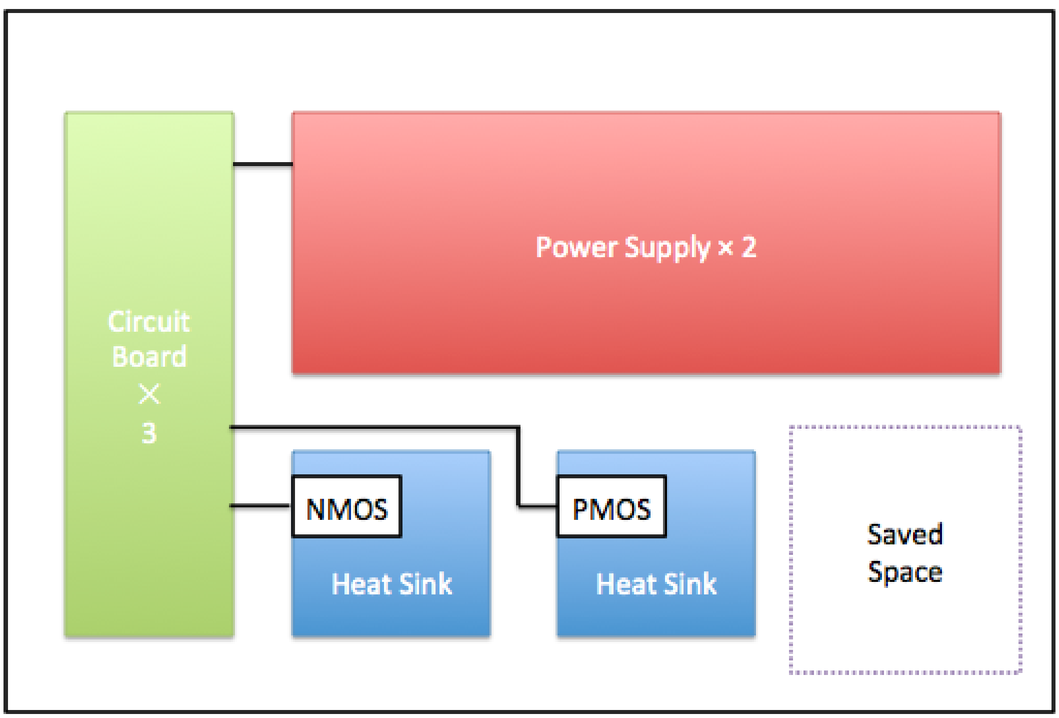


Figure 9. Project Box Structure

3.2 Peltier-thermistor Platform

Since Peltier generates temperature difference on its two surfaces, while one surface is used to control the temperature of the petri dish, the other has to be attached to a large heat sink to distribute the heat. Two banana plugs are attached to the input wire of the peltier plate so that it can be connected to project box. The thermistor is put on the one side above the peltier plate. The material I used to support the thermistor can be bend over so that the position the thermistor probes to the petri dish can be adjusted by hand. Another two banana plugs are attached to the thermistor to connect to the project box. The picture of this peltier-thermistor platform can be found in Appendix A

3.3 Stand-alone Program

Since the computer in student lab of neurobiology doesn't have MATLAB installed, a conversion is needed to make MATLAB script a stand-alone program. Otherwise, purchasing MATLAB will increase the total development budget. MATLAB's deploy tool and its MCC compiler is a good way to convert script to either .exe for windows or .app for MAC. It converts the script as well as packages it with its GUI library so that a GUI interface can be running on a computer without installing MATLAB. I tested the windows OS. The whole package appears as a .exe file and when it is running it automatically installs the compiler and related libraries before calls the GUI. This solution has been tested well on computers which have no MATLAB installed. The detail method can be found on MATLAB's official webpage under deploy tool.

4. Tests and Results

4.1 Maximum Output Voltage Test

In section 2 it states that the actual output voltage after power amplifier is -6V ~ +6V. Since both CMOS and peltier plate may generate heat during the device running, this maximum voltage has to be tested to guarantee the device can stand the maximum voltage for a long period of time. The time period is set to 10 minutes. The results shows that there are no problem for NMOS and the pletier plate, but the PMOS is overheated and has potential risk to burn out. As a result, several smaller voltage are tested and it turns out -4.5V is the maximum voltage PMOS can stand. Modification is then made on microcontroller to set threshold on lowest output voltage so that the maximum negative output control voltage is -4.5V.

4.2 Tuning PID Parameters

Using the method described in section 2, PID controller is tuned under constrains discussed in section 4.1. The final value of PID used for the project is listed as follow:

$$P = 10$$
$$I = 50$$
$$D = 500$$

Under this set of parameters the final product' performance is listed below:

- Cost: 94.01$

- Rising time: 5s /℃ (settled within 10 s)
  Falling time: 10s/℃

- Temperature range: 15 ~ 35 ℃

A comparison between the data above and the original design specification shows that the performance requirements are satisfied. The development cost can be found in Appendix B.

5. Conclusion

The first version of the “Peltier Temperature Controller” has been built and packaged completely. The device has been tested with different computers and worked well. All the device specification satisfied the design goal and with a User Manual in Appendix A, students can easily learn how to use it to conduct related experiments.

For possible future improvement, a better PMOS may be considered to use to increase the maximum positive voltage. A fan can be added to distribute the heat inside the project box more effectively. The Cable connected between project box and the peltier plate can be upgraded both in length and robustness. An LCD screen can be added on the project box so user can use the device without a computer.

6. Acknowledgement

I would like to thank Professor Bruce Land who served as my MEng field advisor. His insight full guidance and suggestions always helped me to move forward every time I got stuck by technical difficulty. His course ECE4760 and ECE5760 also enlighten my understanding on digital system design which has positive effect on this project. I appreciate his dedication and commitment to this project.

I would also like to thank Professor Bruce Johnson who served as my MEng outside advisor. Our meetings were critical for me to calibrate the performance and the future design goal of the project. He also introduces biology knowledge that is outside my major to me, which I found very interesting.

7. Reference

Paper:

[1]Correges P, Bugnard E, Millerin C, Masiero A, Andrivet JP, Bloc A, Dunant Y (1998) A simple, low-cost and fast Peltier thermoregulation set-up for electrophysiology. *J Neurosci Methods* 83:177-184.

[2]Forsythe ID, Coates RT (1988) A chamber for electrophysiological recording from cultured neurones allowing perfusion and temperature control. *J Neurosci Methods* 25:19-27.

[3]Kingsley RE, Barnes CD, Pompeiano O (1976) A proportional controlled thermoregulator circuit of simple design*. Electroencephalogr Clin Neurophysiol* 40:306-308.

[4]Jimena Bemi, Alistair M.Muldal, Stefan R. Pulver, Using Neurogenetics and the Warmth-Gated Ion Channel TRPA1 to Study the Neural Basis of Behavior in Drosophila, *J Undergrad Neurosci Educ*. 2010 Spring; 9(1): A5-A14

[5]Rose G (1983) A temperature controller for in vitro recording chambers. *Brain Res Bull* 10:713-714.

[6]Tools for Physiology Labs: An Inexpensive Means of Temperature Control, Jacob L.Krans and Ronald R.Hoy, *the Journal of Undergraduate Neuroscience Education*, fall 2005, 4(1) A22-A26

Datasheet:

[7]Atmel mega1248 Microcontroller

[8]IRF 9522 P-Channel Enhancement-Mode Vertical DMOS Power FETs

[9]IRF 520 Power MOSFET

[10]LM 358 Low Power Dual Operational Amplifiers

[11]R/2R Series Thick Film Networks

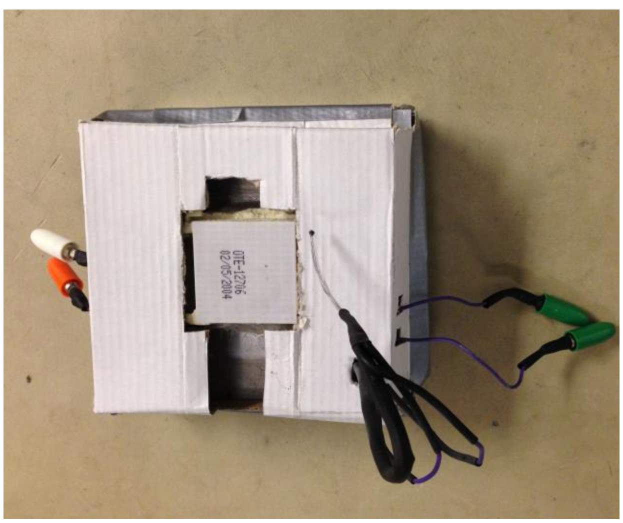
[12]44105 Thermistor with FEP Sheath

Appendix A User Manual

1. Components

Project Box

Cable



Peltier-thermistor Platform

USB cable

2. Connection

1> Connect one end of the yellow-head cable to the green banana sockets on the Peltier-thermistor platform. Connect the other end of the cable to the green banana sockets on the project box. The orders of which plug match which socket doesn't matter.

2> Connect one end of the red-white-head cable to the red-white banana sockets on the Peltier-thermistor platform. Connect the other end of the cable to the red-white banana sockets on the project box. Note that red plug should match the red socket and the white plug should match the white socket.

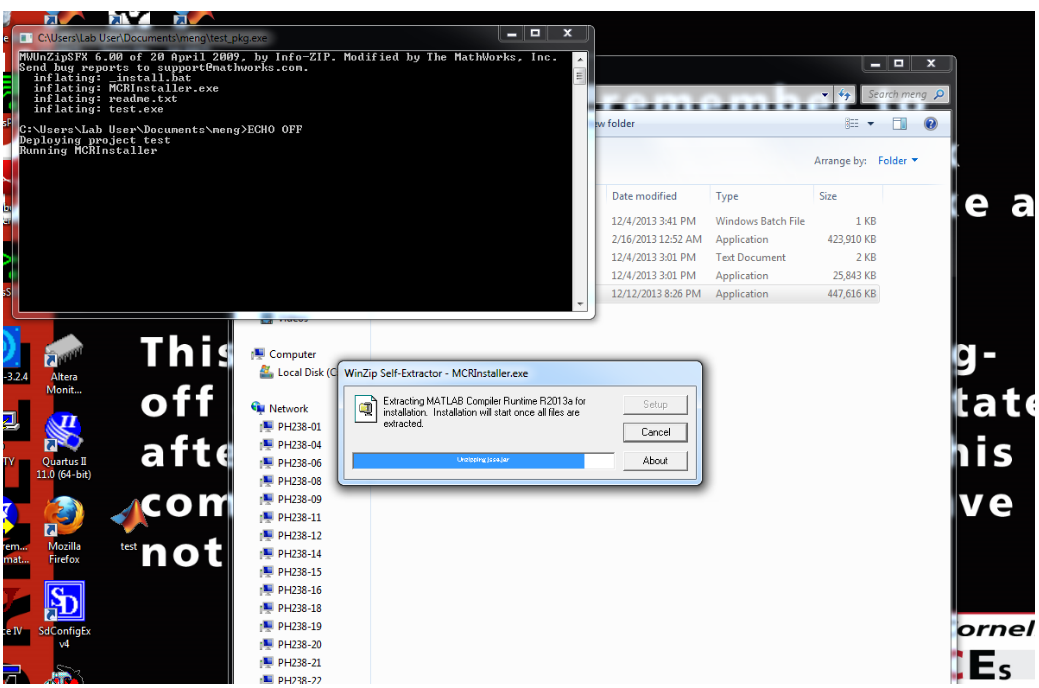
3> Connect the USB port on the project box to a computer by the USB cable.

4> Plug in the power. If the red light on the project is on, the system is ready to work.

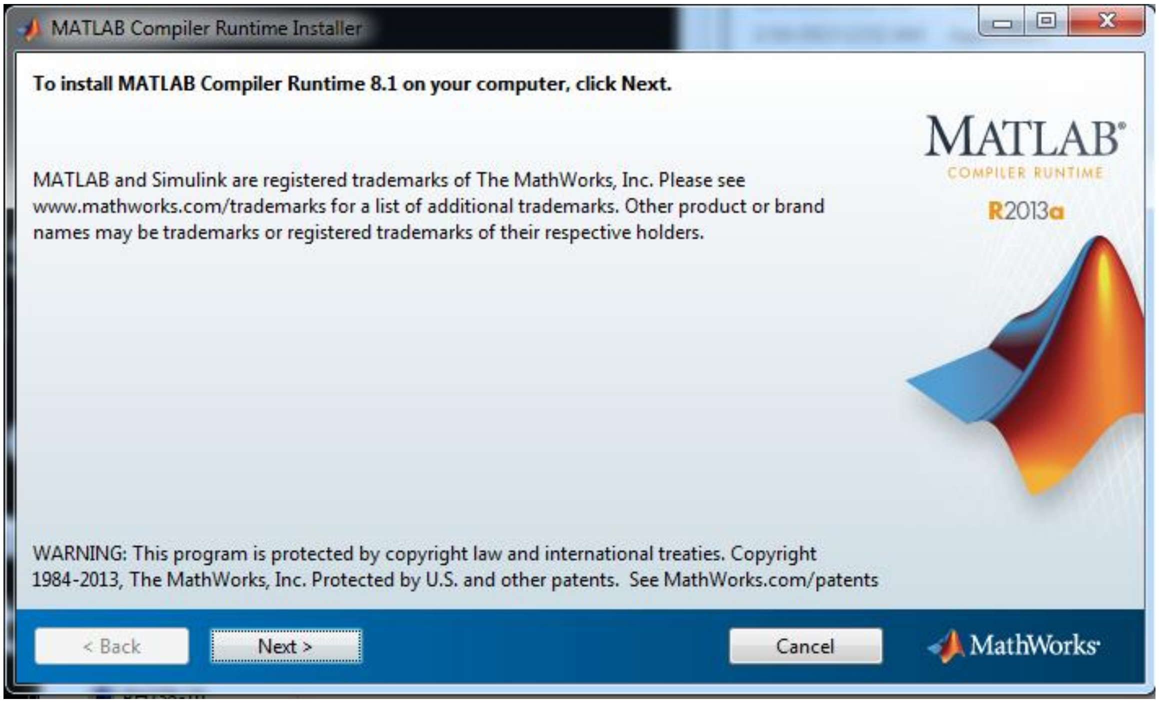
IMPORTANT: DO NOT OPEN THE PROJECT BOX ANYTIME WHEN POWER IS ON!!!

3. Install Software

Double click the test_pkg.exe file. It will automatically extract the MCC compiler and the libraries inside this file as the following picture shows:



MCC compiler has to be installed before using the MATLAB GUI interface. After the extraction, the program will start to install MCC compiler. An installer window will show as the follow:



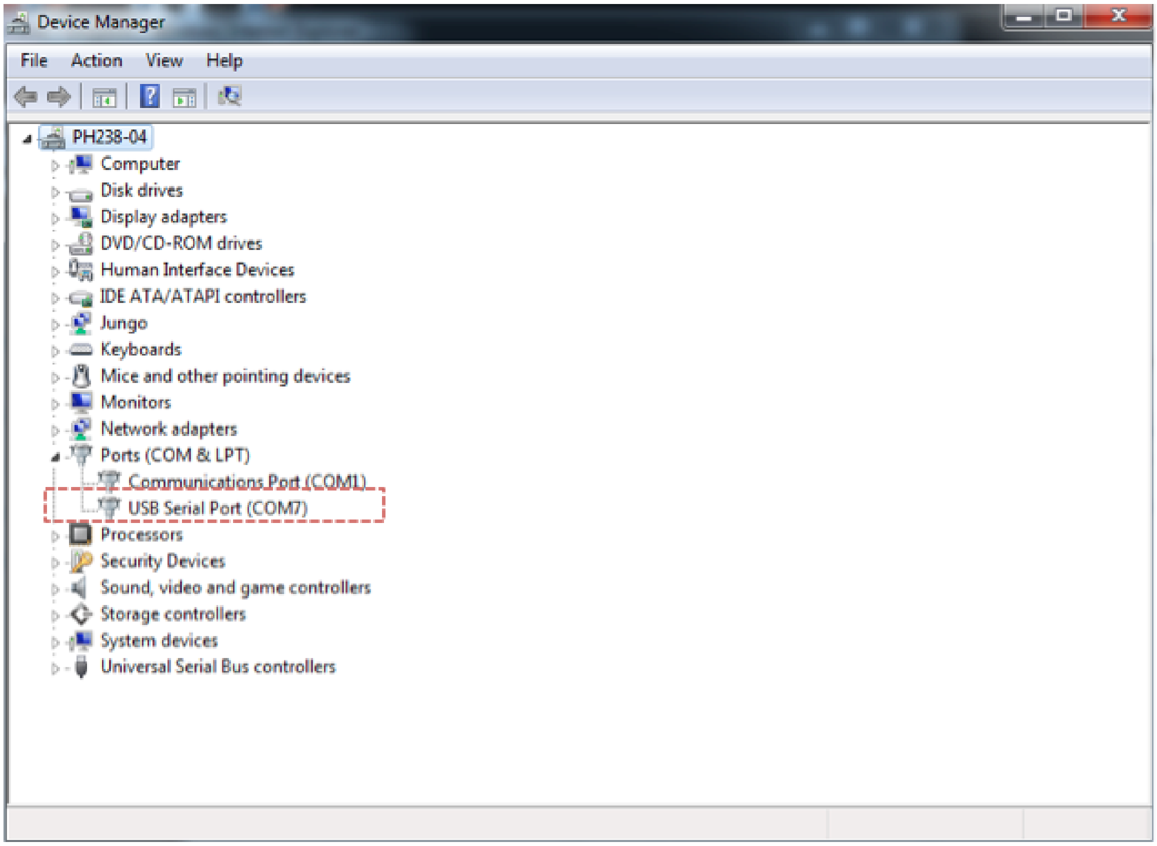
Click Next and follow the instruction in the installer window to finish installing process.

After completion the install, in addition to the test_pkg.exe file, following files will be shown in your document: MCRInstaller.exe (the compiler installer), readme.txt, and test.exe.

Double click the test.exe, the GUI interface should be shown on your computer. (You may have to wait for a while when the program is responding)

4. Running the System

1> Click `Control Panel...System...Hardware Tab...Device Manager Button...+Ports` to find out which serial port is connected to the USB dongle. For example, the following figure indicating the use of a COM7 port.



2> Input the port ID found in step 1> into the bottom right corner in GUI. Press "set" button.

3> Press "detect" button, the current bath temperature of petri dish will be shown in the middle bottom text box.

4> Input the desired temperature in the left bottom corner text box. Press "start" button. The device will start running and you should see the current temperature change both in the middle bottom text box and the dynamic plot.

5> Press "stop" button to stop the current process. And then another desired temperature can be input and repeat step 4>.

6> Press "quit" button when you finish the experiments.

Appendix B Cost

Iterm	Unit Cost	Quantity	Subtotal Cost
Atmaga 1248	$5.00	1	$5.00
Project Box	$29.95	1	$29.95
Peltier+Heat Sink Module	$10.00	1	$10.00
12 V Power Supply	$21.98	2	$43.96
IRF 9522	$1.20	1	$1.20
IRF 520	$0.30	1	$0.30
LM 358	$0.40	3	$1.20
4116 R2R	$0.40	1	$0.40
		Total	$92.01

Appendix C Microcontroller Source Code

```
#define F_CPU 16000000UL
#include <inttypes.h>
#include <avr/io.h>
#include <avr/interrupt.h>
#include <stdio.h>
#include <avr/eeprom.h>

// serial communication library
#include "uart.h"

FILE uart_str = FDEV_SETUP_STREAM(uart_putchar, uart_getchar, _FDEV_SETUP_RW);

#define begin {
#define end }
#define nopress 1
#define maybe     2
#define pressed 3
#define maybeno 4

unsigned char inchar;
volatile unsigned char sw0,sw1;
char des_temp;
volatile unsigned char blinktime;

volatile unsigned char sw, sw0, sw1;
volatile unsigned char swState;

volatile unsigned char swtime;
char temp;
char temp2;

ISR (TIMER0_COMPA_vect)
begin
        //switch detection state machine

        swtime++;
        if (swtime==30)
        begin
            swtime=0;
            switch (swState)
            begin
            case nopress:
                        if (PINB!=0xff)
                  begin
                        swState=maybe;
                        sw = PINB;
                        end
                  break;
```

```
          case maybe:
               if (PINB==sw)
               begin
                    swState=pressed;
                    sw = PINB;
                    sw0 = sw0 + (char)((~sw & 0x80)>0);
                    sw1 = sw1 + (char)((~sw & 0x40)>0);
               end
               else swState=nopress;
                 break;
          case pressed:
               if (PINB==sw) swState=pressed;
               else swState=maybeno;
                    //sw = PINC;
                    break;
               case maybeno:
               if (PINB==sw) swState=pressed;
               else swState=nopress;
                    //sw = PINC;
                    break;
               end //case
       end   //button state machine


       //blink the LED to show it is running
       blinktime++;
       if (blinktime==200)
       begin
          PORTD ^= 0x04 ;
          blinktime=0;
       end //blink routine

end // timer 0 ISR



void main(void)
begin
       //UCSR0B = 0b00011000 ; //hex 0x18
//     UBRR0L = 103 ; //using a 16 MHz crystal (9600 baud)
        //init the UART -- uart_init() is in uart.c
     uart_init();
     stdout = stdin = stderr = &uart_str;
     fprintf(stdout,"Starting...\n\r");

   //crank up the ISRs

       //set up timer 0
       OCR0A=249;                    //1 mSec
     TIMSK0= (1<<OCIE0A);  //turn on timer 0 cmp match ISR
        //set prescalar to divide by 64
```

```
    TCCR0B= 3;
    // turn on clear-on-match
    TCCR0A= (1<<WGM01) ;

    //   blink port
    DDRD = 0x04;   // and d.2 which runs another LED

      DDRA   =   0xff;//test led ports
      PORTA = 0x00;

    // switch port
      DDRB = 0x00;
    PORTB = 0xc0;   // turn on pullups on d.6 and d.7 for pushbuttons

    //set state machine
    swState = nopress;
    sw0=0;
    sw1=0;

    sei();
     while(1)
     begin
            temp = UCSR0A&0x80;
         if (temp)
         begin
              inchar = UDR0 ;
              //fprintf(stdout,"%d   \n\r", inchar) ;
              if (inchar=='s')
              begin
                   //fprintf("%d %d\r\n", sw0, sw1);
                   fprintf(stdout,"%d %d \r", sw0,sw1) ;

                   //fprintf(stdout,"%d   \n\r", sw) ;
                   sw0=0;
                   sw1=0;
              end else if(inchar >=48 && inchar < 100)//second higher bits is check bit
              begin
                   //fprintf(stdout,"%c \r", 'k');
                   des_temp = inchar-48;
                   PORTA = des_temp;
              end else if(inchar>=100&&inchar<110)
                   begin
                   //fprintf(stdout,"%c \r", 'k');
                   //des_temp = inchar-128;
                   des_temp = 7;
                   PORTA = des_temp;
                   end
         end
     end   //while(1)
end //main
```

Appendix D MATLAB Script

```
%UI interface for temperature controller

clf
clear all
try
    fclose(instrfind) %close any bogus serial connections
end

%set(gcf,'CloseRequestFcn','delete')


%define the plot button
start_button=uicontrol('style','pushbutton',...
    'string','Start', ...
    'fontsize',12, ...
    'position',[100,400,60,20], ...
    'callback', 'start=1;');

%define the detection button
detect_button=uicontrol('style','pushbutton',...
    'string','detect', ...
    'fontsize',12, ...
    'position',[200,400,50,20], ...
    'callback','detect=1;');


%define non-editable text field for showing current temperature
current_temperature=uicontrol('style','text',...
    'string','', ...
    'fontsize',12, ...
    'position',[220,1,100,40]...
    );

%define edibale text file for inputing desired temperature
desired_temperature=uicontrol('style','edit',...
    'string','0', ...
    'fontsize',12, ...
    'position',[100,1,100,40] ...
        );

%define edibal text field for setting communication port
communication_ports_set=uicontrol('style','edit',...
    'string','COM1', ...
    'fontsize',12, ...
    'position',[400,1,100,40] ...
        );

 %define the set button
```

```
setbutton=uicontrol('style','pushbutton',...
    'string','Set', ...
    'fontsize',12, ...
    'position',[500,1,50,20], ...
    'callback','set_C=1;');




%define the quit button
quitbutton=uicontrol('style','pushbutton',...
    'string','Quit', ...
    'fontsize',12, ...
    'position',[500,400,50,20], ...
    'callback','quit=1;close;');

%define the stop button
stop_button=uicontrol('style','pushbutton',...
    'string','stop', ...
    'fontsize',12, ...
    'position',[300,400,50,20], ...
    'callback','stop=1;');




%make some axes
axeshandle = axes(...
    'position',[.2 .2 .7 .7],...
    'xlim',[0 100],...
    'ylim',[-20 60]);

%initiate button signals
quit=0; %wait for a quit button push
set_C=0;
start=0;
plus = 1;
neg = 0;
detect =0;
stop =0; %wait for a stop command
setbkgnd=0;
saveit=0;
num_s = 0;
flag = 1;
%null out x and y
x=[];y=[];
bkgndcolor = [1,1,1];
time = 0;
frame_begin = 0    ;
frame_end      = 100;
```

```
frame_limit = 99;



while (quit==0)
   pause(1)
   %//////drawnow; %need this in the loop for controls to work

   if ((set_C == 1) && (flag == 1))
     flag = 0
      %=====open a serial connection=================================
      %set its rate to 9600 baud
      %SR830 terminator character is   (ACSII 13)
      %use fprintf(s,['m' mode]) to write
      %and fscanf(s) to read the SR830
     port = get(communication_ports_set,'string');
     s = serial(port,...
        'baudrate',9600,...
        'terminator',13);
    fopen(s)
   end
     if (flag == 0)

       if start==1
          start=0;
          Switch = 0;
            des_temp = 48+str2num(get(desired_temperature,'string'));

          fprintf(s,des_temp)

       end

       if detect==1
            fprintf(s,'s')
            Switch = fscanf(s,'%d%d')
            num_s = Switch(1) + Switch(2)/10;
            plot(time,num_s,'--rs','LineWidth',2,...
                    'MarkerEdgeColor','g',...
                    'MarkerFaceColor','g',...
                    'MarkerSize',2),grid on;

            hold on;
            if(time>frame_limit)
                  frame_begin = frame_begin + 100      ;
                  frame_end     = frame_end + 100         ;
                  frame_limit = frame_limit + 100       ;
            end
            axis([ frame_begin frame_end -20 60]);
            time = time +1;
```

```
                set(current_temperature,'string',num2str(num_s));

        end

        if stop==1
            stop     = 0;
            detect = 0;
            set(desired_temperature,'string','0');
            set(current_temperature,'string','0');
            fprintf(s,'t')
        end
    end



end
if(flag == 0)
  fclose(s)
end
```