CONTROL SYSTEM FOR THE SOLAR HOT WATER COLLECTION ALTERNATIVE SYSTEM OF CORNELL UNIVERSITY SOLAR DECATHLON

A Design Project Report

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Master of Engineering (Electrical)

by

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Abstract

Master of Engineering Program

Cornell University

Design Project Report

Project Title: Control system for the solar hot water collection alternative system of Cornell University Solar Decathlon

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Abstract: This project is a component of the Cornell University Solar Decathlon which is dedicated to building a solar powered house to collect and save as much energy as possible using various methods including solar hot water collection. In the alternative system this project focuses on, solar hot water is collected in the copper coil under the corrugated steel peripheral of the house. The goal is to design a control system using microcontroller to control the pump and the valves connected to the coil based on the temperature of the coils and the hot/cold water tanks monitored using digital temperature sensors. There is a computer interface for users to setup desired threshold temperature, and control the pump and valves either automatically or manually. Atmel ATmega644 microcontroller was used as the control unit for the project.

Report Approved by
Project Advisor: ______________________________ Date: _____________

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Executive Summary

This project is the control system of the alternative system which uses copper coils under the corrugated steel peripheral of the house to collect the heat from the sun. The heated solution inside the coils will be pumped through the heat exchanger connected to the hot water tank. Initially, the system was designed to have 6 or 8 different sections located on different positions of the wall; whenever the temperature in any of the section is higher than the threshold temperature, the pump would start pumping and the corresponding valves would open according. However, due to construction delay and cost overruns, the hardware was modified and there was only one section left to collect heat from the sun, and the valves for different section were removed since there was only one route in the system.

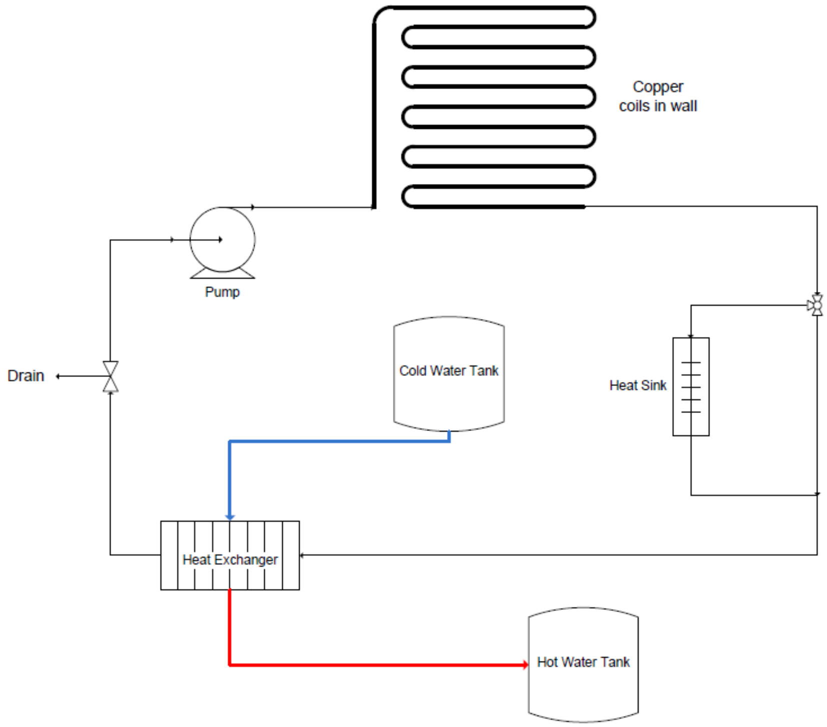
The control system includes an ATmega644 MCU, two digital temperature sensors, a TACO-007 pump, two electrical actuated valves for the heat sink, and a computer-based user interface. The pump will be turned on and off based on the current temperatures of the coils and the cold water tank, and the threshold temperature set by the user. Through the user interface, the user is able to turn on and off the pump manually and monitor the system status.

The outcome of the project was a success. All functionalities were implemented and fully tested, and will be installed in the house during its construction.

1. Introduction

The Solar Decathlon is an international design-build competition hosted biennially by the U.S. Department of Energy. Twenty college and university teams compete to design, build and operate the most attractive, effective and energy-efficient solar-powered house. Different parameters are being recorded during the competition and used to evaluate the overall performance of every team. The solar hot water collection is one of the main performance measures, and it consists of two systems to maximize the efficiency.

The alternative system this project focused on can be expressed in the following system diagram:

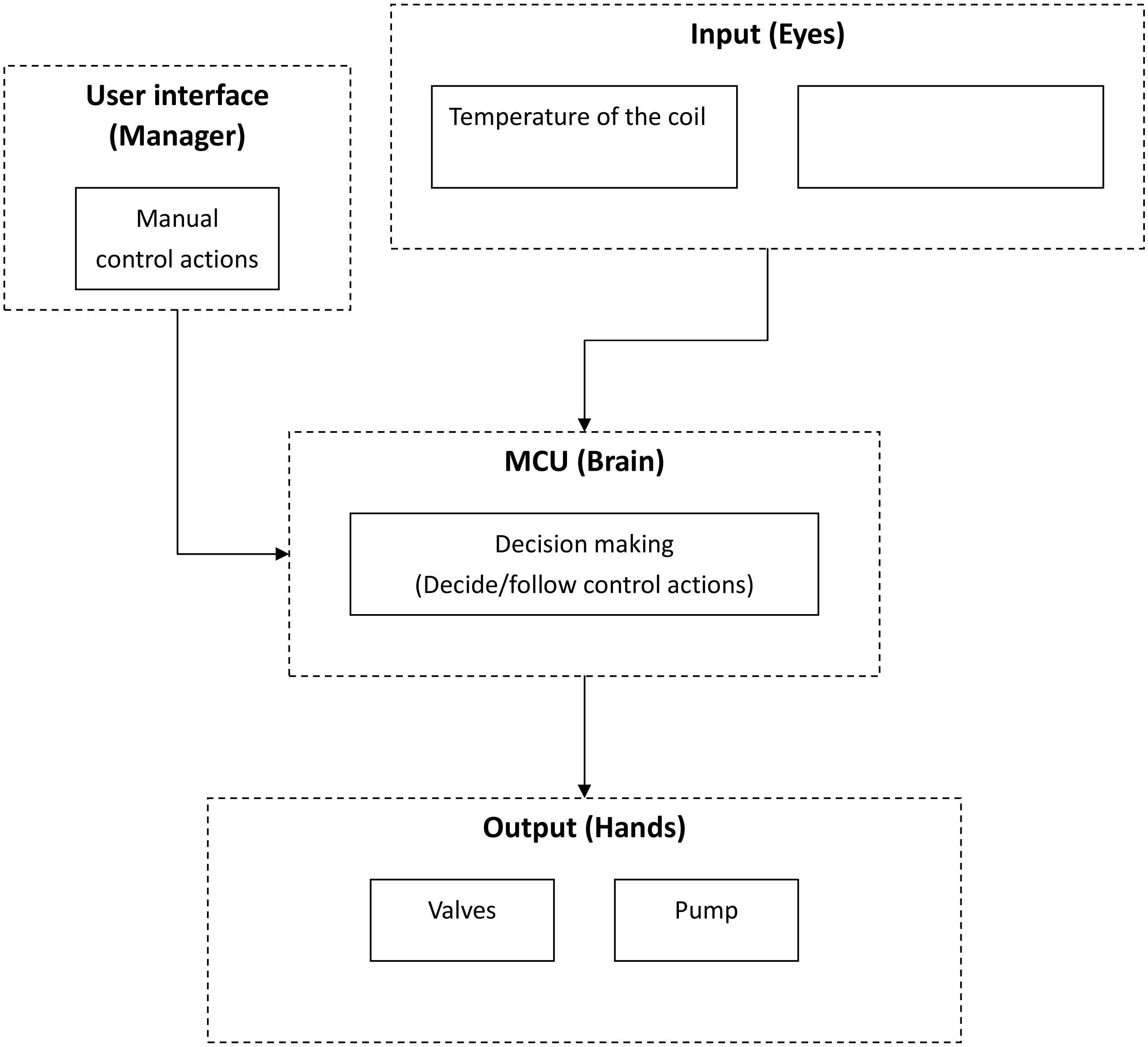


The main components of the system hardware include

1. Copper coils in the wall
2. Cold/Hot water tank
3. Heat exchanger
4. Heat sink with electrical actuated valves
5. Pump
6. Manual drain valve

These components are the output of the whole system; they are like the hands of the system. To enable the system to operate automatically and intelligently, a microcontroller was used as the main processor of the control system; it is like the brain of the system. Besides the microcontroller as the brain, 2 temperature sensors are installed on the copper coils in the wall and the cold water tank as the input of they system; they are like the eyes of the system. Lastly, there is a computer user interface which is connected to the microcontroller via serial port (or USB) to setup threshold temperature and to execute other manual control options; this is like the manager who gives instruction to the system.

The logical diagram of the system below may express the idea more clearly.



Therefore, to achieve the functionalities, the project can be separated into 4 parts: input, output, MCU, and the user interface. They were done separately at the beginning and integrated after every single part works alone perfectly.

The MCU used in this project was Atmel ATmega644, which is the control unit introduced in the course ECE 4760 by Dr. Bruce Land.

2. Design Requirements

Since this project served as the control system of the alternative system in Solar Decathlon, it would have to meet the requirements given by the solar thermal sub-team of the Solar Decathlon Engineering Team. That is, the control system will be depending on the hardware specifications.

Initially they were planning to install 6 or 8 sections of copper coils around the peripherals of the house. However, due to construction delays and cost overruns, the specifications have gone through several modifications during the course of the year. For the initial hardware design, there would be either 6 or 8 sections, which meant that the system would have to scan through 6 or 8 temperature sensors and turn on different sets of valves based on its temperature. The solar thermal team finally settled on only 1 section because of construction time and budget constraints. As a result, the idea of valves was removed since there is no other section to select from. They also added a heat sink route for safety reason to prevent overheating which also required a set of valves. The general control logic they required stayed the same: the pump will be turned on whenever the temperature reaches the threshold, and turned off when the temperature drop close to the temperature of the cold water tank.

The general requirements of the control system are finalized as the following:

1. The system should automatically turn on the pump when the temperature of

the coil reaches **the threshold temperature**.

2. The system should automatically turn off the pump when the temperature of the coils drops below "**the temperature of the cold water tank plus 2 degree C**"
3. The system should automatically turn on the valves that lead to the heat sink when **the temperature rises above 99 degree C**.
4. User must be able to view the current status of the valves, pumps, and the readings of different temperature sensors from the user interface.
5. User must be able to set the threshold temperature.
6. User must be able to control the valves and the pump manually regardless of the current status and temperatures.

The final completed system also includes some minor functions which are not stated above such as false input parameter prevention, Celsius/Fahrenheit conversion, and temporary suspension of the control actions.

The biggest problem I encountered in doing this project is that the electrical actuated valve needed for the heat sink route was very expensive and would have exceeded the budget. At the end of this project, the business sub-team was still trying to get the valves donated. Therefore, in this project, a fan was connected to the FET as a substitute for the valve to test the control functionality.

3. Possible Solutions

To create the control system, I would have to choose a microcontroller (MCU), a temperature sensor, and a form of user interface. The selection of the valves is determined by the donation we could get, and the pump TACO 007 was previously determined by the solar thermal team. The MCU will have to read the temperature sensors and create a user interface, and the temperature sensor should better have a digital output to avoid noise in analog signal which happens a lot especially when the connection between the MCU and the sensors is long. The user interface must be easy and straightforward. Everyone with or without electrical engineering background knowledge should be able to operate the system through the interface even without a user manual.

3.1. <u>Microcontroller</u>

The microcontroller Atmel ATmega644 used in the ECE4760 course turned out to be to best choice for this project. It can be programmed in C, it is readily available and there are plenty of resources about the MCU in the course website. Prototype PCB and necessary components for the MCU are all readily available in the ECE4760 laboratory. Although I had never used the MCU when I started the project, I believed that I would become more and more familiar with it since I was taking the course starting at the same time.

3.2. Temperature sensors

As stated above, the temperature sensor should come with a digital output. Handling analog signal involved noise problem which are not the main thing that this project was focused on. Therefore, a digital output sensor would save me from worrying about noise and analog to digital conversion.

The temperature I am dealing with in this project has a range of 15°C to nearly 100°C. Since the on and off threshold temperature are always differentiated by at least 30°C, it does not require a very high accuracy; therefore a ±2°C accuracy is acceptable. The LM70 digital thermal sensor from National Semiconductor fit the requirements very well. It has a resolution of 0.25°C, accuracy of ±2°C, and the max/min temperature are -55°C /150°C. It comes with internal ADC, and SPI/Microwire compatible interface. The ATmega644 microcontroller has a built-in SPI bus, which makes it very easy to interact with the sensor. The package options are LLP and SOIC. I chose SOIC because I would have to solder the IC on a breakout board, and an IC with lead is much easier to handle. Luckily, National Semiconductor provides a small number of free samples of these sensors so I ordered some samples when I began to work on this project.

3.3. User interface

For the user interface of the control system, I initially pictured a system with a keypad with a 2-lined LCD display by its side. The user could use the keypad to choose from different control options and view the current status of the system. This would be a compact interface because the user will be able to manipulate the system without any external device; however, the input and output interface were both limited because of the size of the keypad and the small LCD.

The other option which I decided to use was a computer interface with UART communication to the MCU. I thought about this option when I was working on one of the lab assignment of the ECE 4760 course. The MCU will work independently without the computer, and whenever the user want to monitor or control the system, he or she can simply connect the USB cable to a laptop and run the hyperterminal program which is included as a default program in all the Windows XP operating system. The USB cable is actually a USB/Serial dongle that goes to the serial port of the MCU. With a laptop, the user will be able to operate the system more easily. After the program and the connection are setup correctly according to the user manual, all the temperature readings and the status can be seen in one screen without the need of changing pages. The interface will explain itself so that the user can manipulate the system without a user manual.

3.4. Valves and pump actuating

The choice of valves and pump was not under my control as they are determined by other teams. I will be controlling the valve using FET and the pump using a solid state relay. Both of the circuit will be isolated from the MCU using optoisolator to prevent from spikes feedback to the MCU.

3.5. Final project definition

The definition of the final project is as following. The ATmega644 will be used to receive the input data from the temperature sensors and decided necessary control options to the output of valves and the pump. The LM70 digital thermal sensors will be used to monitor the temperature of the coil and the cold water tank. A serial/USB connection cable will be available by the control system for the user to connect a laptop to interact with the system. The valves and pump are decided by other sub-teams, and they will be controlled by the MCU using FET and solid state relay and isolated using optoisolator. The project definition satisfies all the project objectives. The next part of the report will focus on the detailed design of the project.

4. Design

The design of the control system can be divided into 3 parts: **input, output, and MCU**. In the following part of the report, the software design and hardware construction of each part will be discussed.

4.1. <u>Input</u>

The input of the control system is the **LM70 temperature sensors**. The dimension of the SOIC package is approximately 3 x 3 x 0.86 mm^3; it is a surface mount device with 8 leads. I first have to solder the IC on to a breakout board. It was my first time to deal with a surface mount device and the very first one did take me a while to finish. Luckily the soldering part looks successful and I could start testing the sensor with the MCU.

The LM70 has a SPI/Microwire compatible interface. SPI is a three-wire, synchronous, and serial protocol, and most of the AVR MCUs have a hardware support for it. The three wires of SPI are master-in-slave-out, master-out-slave-in, and clock. For the Microwire on LM70, it is actually a two-wire protocol: SI/O (serial input/output) and clock. The principles are basically the same but Microwire use the same wire for input and out. Besides the SI/O and clock on the chip, it also has a Chip Select (inverted) pin for the master to select from different device. In this project I am using 2 SPI-interfaced temperature sensors, so 2 pins (pin 3 and pin 4) from PORTB of the MCU are respectively connected to the Chip Select pin on the two sensors. SPI is essentially a synchronized serial protocol. When the master (in this case the MCU) is ready to send data to the slave (the sensors), the program will put an 8-bit data into the shift register SPDR. The transmission will then begin and the data from the master will be shifted into the register in the slave, and vice versa. After the transmission is completed, the data from the slave will be ready to read in the SPDR register. In the LM70 temperature sensor, it will send a fixed format of data no matter what is received from the MCU. Since it doesn’t do anything with the data it received, I don’t even have to connect the master-out-slave-in pin to the sensor. Therefore in this project, the MOSI pin (PORTB 5) was left unconnected to anything. The clock (PORTB 7) and the chip select pin (PORTB 4) will enable the SPI transmission to work correctly.

After setting up the connection, I had to figure out the necessary setting parameter for the MCU to communicate with the sensor. There are 4 different combinations of SPI data transmission modes. The clock can be set to either high or low when SPI is idle; this can be selected by setting and clearing the CPOL (Clock Polarity) bit in the control register. The data sampling can be set to occur either at the trailing or the leading edge of clock; this can be determined by setting or clearing the

CPHA bit in the control register. Normally in the datasheets of the devices using SPI interface, they would directly state its transmission mode; however, these datasheets were sometimes too complicated. The easiest way to figure out its mode is to try all 4 different modes one by one. Luckily my first try worked and I found that the LM70 sensor has an idle clock of LOW and the sampling is taken place at the trailing edge of the clock (CPOL =1 and CPHA = 1).

LM70 is a 10-bit temperature sensor so the data format is always 2 byte with a sign bit (MSB), 10 data bits, and 5 unused bits. Every time the MCU samples data from the sensor, it has to read 2 bytes back in order to get a complete data. The LSB of the data is the resolution of the sensor, which is 0.25°C in this case. After getting the 2 bytes, the MCU would do the calculation and store the result. I first used LED on the STK500 (the development board for ATmega644) to display the temperature reading and make sure it's getting the right data. To calibrate a sensor, I had to find an external sensor which was guaranteed to be more accurate than the device being calibrated. I borrowed an electronic temperature sensor and measure the temperature near the LM70, and it turned out that the reading was quite accurate with a difference of less than 2°C under room temperature.

According to the datasheet, the LM70 sensor is measuring the temperature of itself, that is, the temperature of the die. For the LM70, the best thermal path between the die and the outside world is through its pins. It will also provide an accurate measurement of the temperature of the printed circuit board on which it is mounted. I tested the sensor under several different circumstances including room temperature, the temperature of human body, and I also used electric soldering iron to raise the surrounding temperature and see if the sensor works correctly in such condition. The test went pretty well and demonstrated that the sensor is capable of reading a large range of temperature with a fast response time.

4.2. Output

The output of the system includes two devices. The pump and the valves connected to the heat sink. Since the valves were not readily available at the moment, I started working on the pump first.

The pump used for the system is Taco 007 Cartridge Circulator. The minimum fluid temperature is 4°C and the maximum is more than 100°C which is good enough to fit the need of this project. The pump run on 110 volts, but it came with no power cable or switch on it. The first thing I need was to open the cover of the power panel and I found 2 wires and a screw that is used to connect the ground wire. Before trying to “control” the pump, I had to make sure that the pump is working properly. To provide AC power to the pump, I used an old computer power cord and cut the female end, and connect the wires respectively to the pump. The darkest wire inside is connected to the hot power, the lightest wire is the neutral wire and the green wire is connected to the ground. 110 volts could be harmful to human if not handled properly, so I would have to make sure all the wires are connected without any mistake. The wire inside the pump is insulated solid wire and the wire in the power cord is stranded wire. They were soldered together with electrical tape wrapping around the connection. After the 2 wires were connected properly and the ground was attached to the screw on the pump surface, I tried to hook up the power cord to a single plug instead of the extension cord in the laboratory. I did this because even if there had been a connection problem between the wires, it would not affect other plugs in the lab. The pump start to run and I removed the plug immediately because the bearings inside the pump are water lubricated and the pump is not supposed to be run dry for too long.

After making sure that the pump works, I started working on the control circuit for the pump. A solid state relay is the best solution for the pump control issue. The solid state I chose was Sharp S216S02 which is used in one of the previous year project of ECE 4760. It has 4 pins; two of them should be connected in series to the power wire of the 110 volts cable, and the other two should be connected to the MCU for sending control signal. The circuit inside the solid state relay was opto-isolated, and it can be operated simply by connecting the GND to the negative pin and the control pin through a resistor to the positive pin.

Since the pump was not supposed to run dry, I built a simple circuit connecting a desk lamp through the relay as a substitute for the pump. I wrote a small program in using the MCU which will set a pin if I push a button. The pin was connected to the relay input and the system was ready to go. The system worked perfectly and I believed the system would represent the actual system with pump very well.

By the time I started working on the control of the valves, there was still no news from the business sub-team. I decided to build the control system using a substitute as I did for the pump to test the control ability first. In one of the lab assignment of the ECE 4760 course, we built a circuit that controlled a 12volts fan with the MCU. The idea of controlling the fan and the valve is identical because the "switch" was implemented using a FET. I built the circuit according to the lab description and it worked as expected.

4.3. **Microcontroller (MCU)**

The job of the MCU in the project was to get the readings from the temperature sensors, make decision based on the input, and send control signal to the valves and the pump. In addition, the user interface was also implemented in pure software inside the MCU program.

First of all, the MCU must be able to read from two sensors. The sensors worked as the slaves in SPI communication and the MCU was the master. Through clearing the Chip Select pin on the sensor chip, the MCU got to choose which sensor could transmit data. The MCU is working as master in this program; therefore I can simply use polling to read from the temperature sensor and no interrupt was needed for this part. The temperature of the coil is increasing approximately at the maximum rate of 1°C per second. The resolution of the sensor was 0.25°C so the sampling rate has to be at least 4Hz to record all the changes in temperature. A task in the program reading the two temperature sensor was scheduled to run every 100 milliseconds, which is equivalent to 10Hz. The data received was translated into degree Celsius and store in variables with `double` data type.

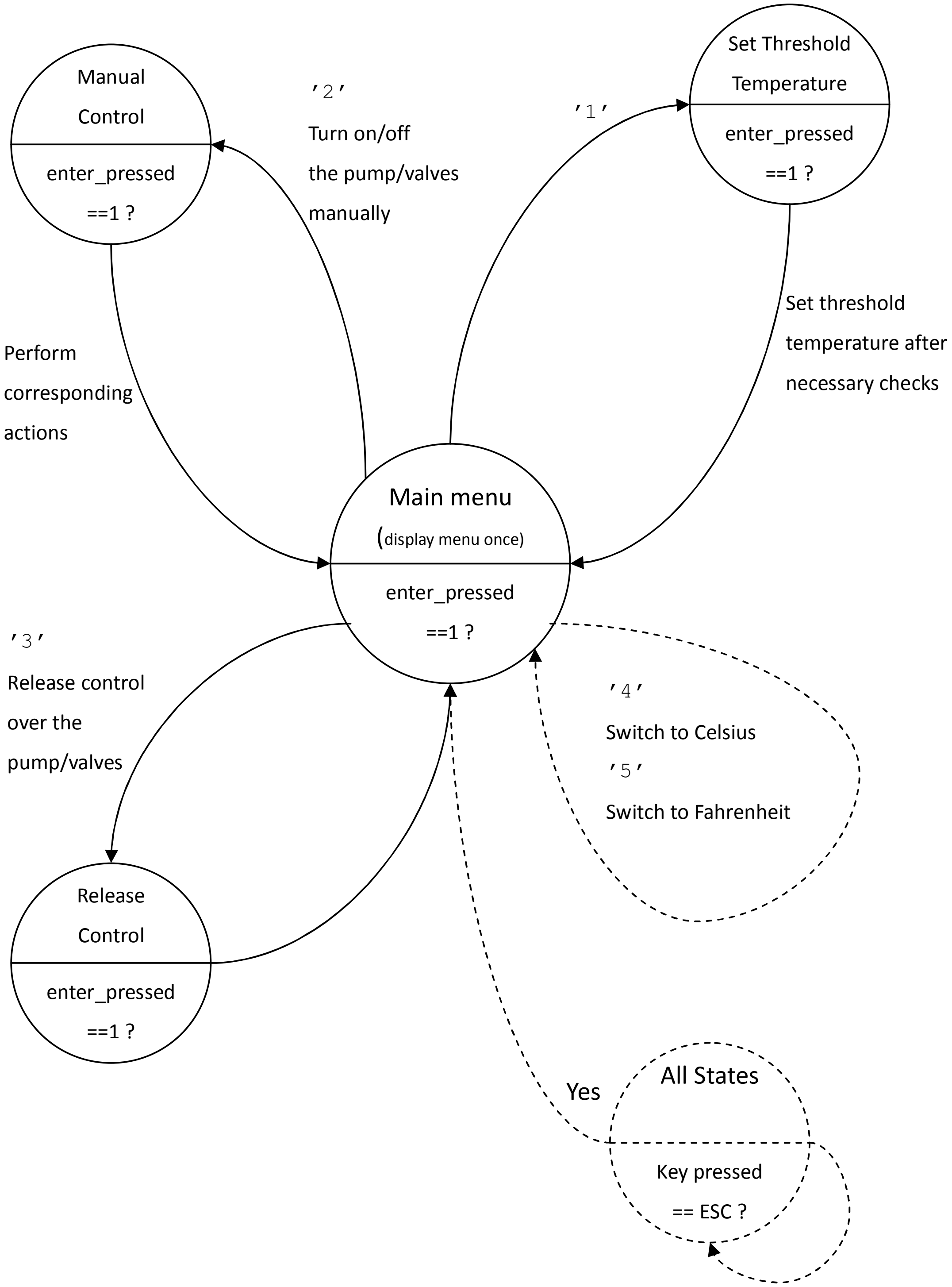
After getting the temperature readings, the program compared the current temperature of the coil to the threshold temperature. If the coil temperature is higher than the threshold set by the user, it would set a pin which turns on the pump. If the temperature drops below the temperature of the cold water tank plus 2°C, the pin will be cleared so that the pump is shut down.

A finite state machine was used in the program to implement the menu-based user interface. The program received input via UART from the laptop connected to the MCU, processed the input message and did the necessary actions. In view of the fact that there will not be a laptop connected to the system at all time, the program cannot use a loop or the `getchar()` function to receive input or the system will stop working and wait for input signal. Instead, the program had an interrupt setup to receive input from the serial port. ATmega644 has a built-in interrupt handle USART0_RX which take care of the job. Whenever the connection is setup and a key is pressed on the computer, interrupt would occur and collect the data coming in. To output data to the hyperterminal on the laptop, there was another interrupt subroutine being responsible for the task. The structure of this part of the program was created in the Lab 3 – security system of the ECE 4760 course. Code of the demo program of the lab was partially adopted in this project. Not all the inputs will be stored and processed but they will first be analyzed to prevent from false input. For example, the space key can sometimes cause a problem when it's stored in a character array. Therefore, the space key is ignored and not stored when it's pressed to prevent any possible mistake.

The finite state machine worked as the core of the user interface. Whenever the user interface is idle or not connected, the state machine is in the `main_menu` state. In this state, the state machine displays the menu once and waits for the user input. The user will be able to view from the top of the menu **the current temperature of the coil, the temperature of the cold water tank, the status of the pump, and the**

status of the valves. Different options are available to choose from by the user including “Set Threshold Temperature”, “Manual Control”, “Release Control”, “Switch to Celsius”, and “Switch to Fahrenheit”. Please refer to the appendix for the image of the user interface. When I was testing the user interface, I found that the menu can be messed up easily by intentionally sending a large amount of input to the system while it’s printing on to the hyperterminal via interrupt. This situation occurs due to the limit of transmission rate of UART. I believed it was necessary to have a “Back to main menu” or “Refresh” key to restore the system back to normal and the key should not go through the finite state machine. In the receive interrupt, I first check the input character before storing it. As stated previously, if the key pressed is space, then nothing will happen. If an ESC key is pressed, the program will then clear the screen and force the state machine to go back to `main_menu` regardless of the current state. Once the program leave the interrupt, the state machine will find itself in the `main_menu` state and display the menu again. The ESC key is also used as the initialization key to begin with when the laptop is connected to the MCU. The code of the state machine was modified from my code of lab 3 in the ECE 4760 course. The following state diagram gives a clear view of the state machine.

State machine of the control system user interface
The state machine stays where it is whenever
enter or **ESC** is not pressed



After implementing the functions on the MCU, I started working on the hardware of it. Initially I was using a STK500 development board to write and test the program. For the final device which is going to be installed in the house, the MCU is installed on a more compact prototype board. The prototype board used is designed by Dr. Bruce Land for the ECE 4760 course. Please refer to appendix for the schematics.

I tested the same program on the board upon its completion. There were 2 major problems I ran into when I was trying to make the prototype board work. First of all, the SPI bus on ATmega644 is hardware-determined on the pin 5, 6, and 7 on PORT B, which happens to be the 3 pins that are used to program the MCU. When any of these 3 pins were driven by an external source during programming, the chip would not program. Therefore I would have to remove the MISO wire at PORTB 6 whenever I was programming the chip. This wasn't a big problem because it was stated in the prototype board description page. However, if I connect the wire back to PORTB 6 after the chip was programmed, the reading of the sensor was still sometimes incorrect. This was because the programming cable may still affect the prototype board because the power of the programmer (STK500) was still on. As a result, I had to make sure that the programming cable is removed to ensure that the MCU receive the correct data from the sensors.

The other problem I had was a hardware problem of the prototype board. When I was soldering header to the output pins on the board, I happened to solder a header falsely into a hole which wasn’t designed for a header connection. It was a ground connection and was simply used to connect the upper layer and the lower layer of the board, and the size was smaller than other ones as well due to this reason. There shouldn’t be any problem even though I inserted a pin to the ground hole. However, I somehow destroyed the connection of the hole and made one of the ground pin disconnected from the GND of the power source. That is, the ground that goes out was not connected to the actual GND properly. I didn’t know this until I keep getting incorrect data from the sensor. A few hours were spent on this problem and I went through all the possible reasons but hardware. Finally I started checking the connection on each pin and found that some of the pins were having a bad connection including the GND. I made sure all the connection were good by desoldering the bad ones and solder it again, but the bad connection on the ground continued to exist. I realized that there’s a connection problem on the PCB rather than the soldered hole. To fix the problem, I found out which one of the inner connection failed and soldered a short wire on the bottom of the board to rebuild the connection. Detailed pictures are included in the appendix.

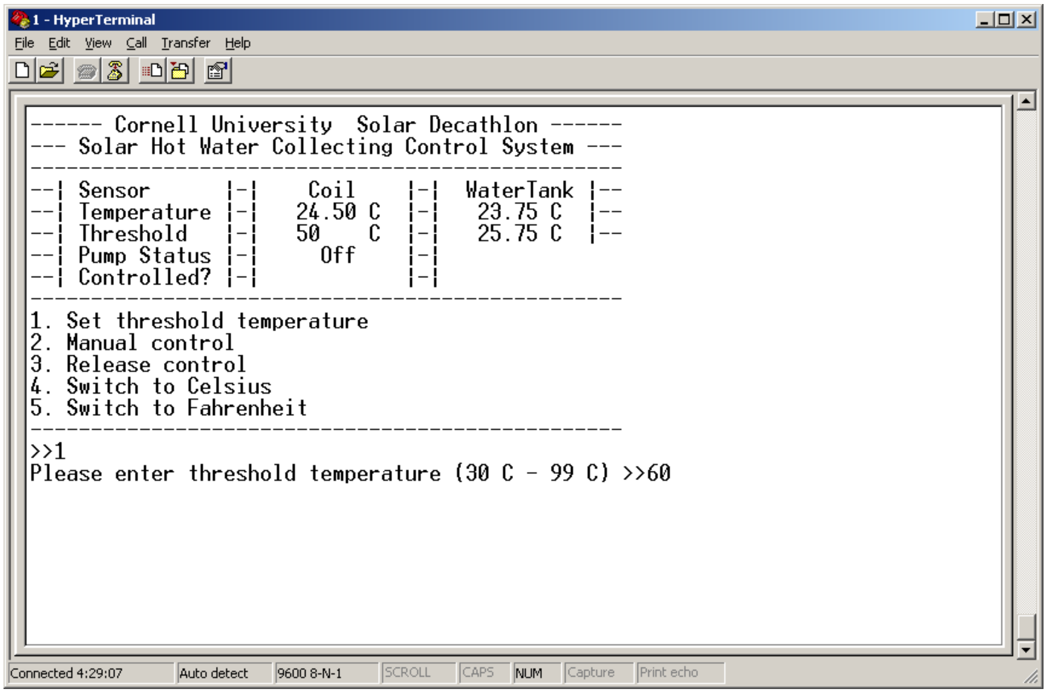
After solving these problems, the prototype board worked as expected and the system prototype was completed.

5. Result

Overall, the results were quite successful. All the required functionalities were implemented in software and hardware except for the electrical actuated valve. The control system including the pump was fully tested upon completion of the project. The user interface is simple and requires only a laptop with USB port and the hyperterminal or other compatible programs. The control system along with the hardware will be installed on to the house during its construction in May 2009.

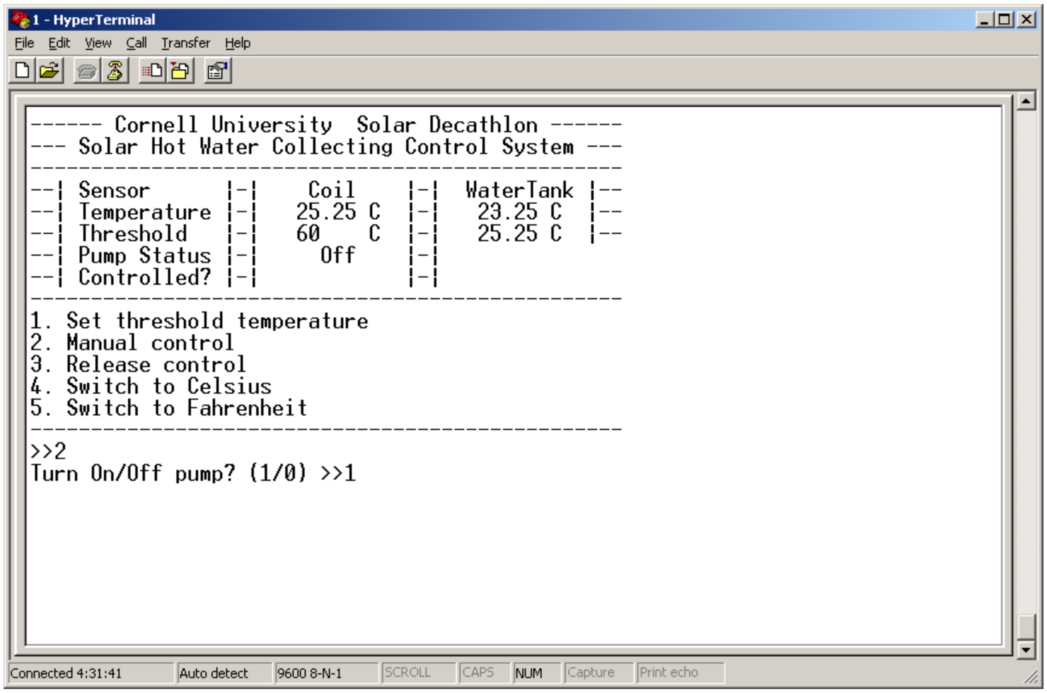
The diagrams below show the user interface.

Setting threshold temperature



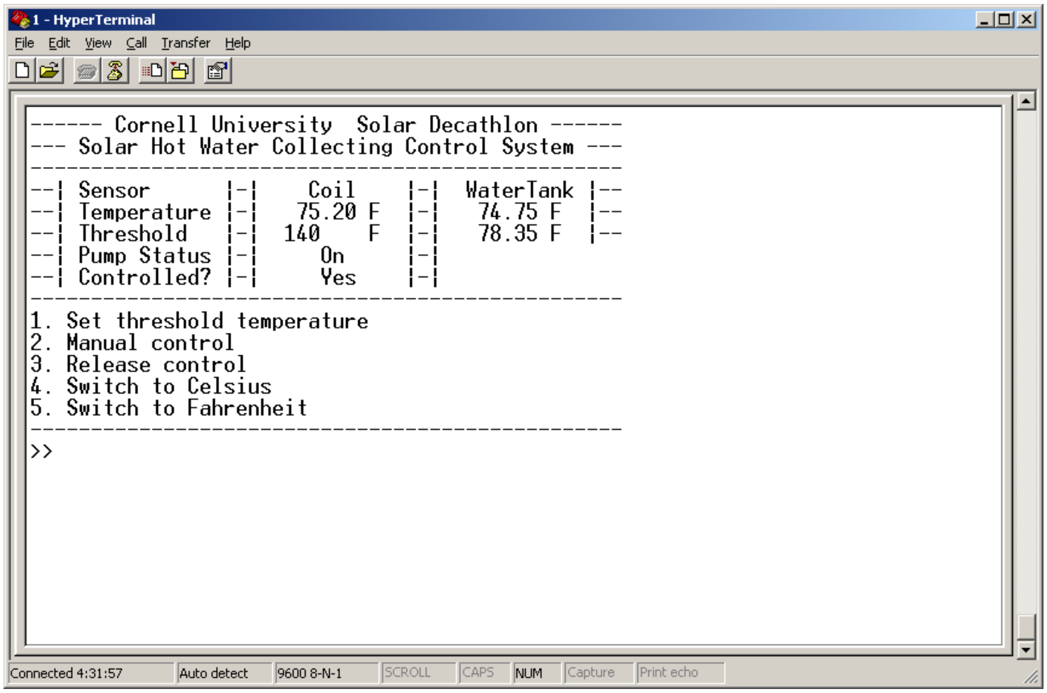
```
------ Cornell University  Solar Decathlon ------
--- Solar Hot Water Collecting Control System ---
-------------------------------------------------
--¦ Sensor      ¦-¦    Coil     ¦-¦  WaterTank ¦--
--¦ Temperature ¦-¦   24.50 C   ¦-¦   23.75 C  ¦--
--¦ Threshold   ¦-¦   50    C   ¦-¦   25.75 C  ¦--
--¦ Pump Status ¦-¦     Off     ¦-¦
--¦ Controlled? ¦-¦             ¦-¦
-------------------------------------------------
1. Set threshold temperature
2. Manual control
3. Release control
4. Switch to Celsius
5. Switch to Fahrenheit
-------------------------------------------------
>>1
Please enter threshold temperature (30 C - 99 C) >>60
```

Manually controlling the pump



```
------ Cornell University  Solar Decathlon ------
--- Solar Hot Water Collecting Control System ---
-------------------------------------------------
--| Sensor      |-|   Coil    |-|  WaterTank |--
--| Temperature |-|  25.25 C  |-|   23.25 C  |--
--| Threshold   |-|  60    C  |-|   25.25 C  |--
--| Pump Status |-|    Off    |-|
--| Controlled? |-|           |-|
-------------------------------------------------
1. Set threshold temperature
2. Manual control
3. Release control
4. Switch to Celsius
5. Switch to Fahrenheit
-------------------------------------------------
>>2
Turn On/Off pump? (1/0) >>1
```

Pump manually turned on (also in Fahrenheit mode)



```
------ Cornell University  Solar Decathlon ------
--- Solar Hot Water Collecting Control System ---
-------------------------------------------------
--| Sensor      |-|   Coil    |-|  WaterTank |--
--| Temperature |-|  75.20 F  |-|   74.75 F  |--
--| Threshold   |-| 140    F  |-|   78.35 F  |--
--| Pump Status |-|    On     |-|
--| Controlled? |-|    Yes    |-|
-------------------------------------------------
1. Set threshold temperature
2. Manual control
3. Release control
4. Switch to Celsius
5. Switch to Fahrenheit
-------------------------------------------------
>>
```

6. Conclusion

It was an excellent experience in the project design process. In terms of technical skills, I have learned to control devices with higher voltages. I was able to do turn on and off a device running at 110 volts, which is very useful because most of the control ideas in daily life involve a high voltage device such as household electronics. I also learned to interface with SPI and improved my circuit building, soldering, and debugging skills. I got to review my previously written code and make improvements, and it made me realize that a program can always be made better by reviewing the whole design again and again. A system is never too good to be improved.

On the other hand, in terms of design experience, my independent research and design ability has increased over the course of the year. When interacting with the project manager and other sub-teams, I learned about the system engineering concepts and a lot of seemingly trivial but actually helpful techniques in communicating and interacting with other people. I also get to see the procedure of building a large-scale project (the whole CUSD), which is very much more organized and standardized than an independent or team project.

Overall, I not only successfully built a control system for the Solar Decathlon but also learned a lot of precious knowledge.

7. Reference

1. LM70 datasheet (National Semiconductor)

2. ATmega644 datasheet (Atmel)

3. Taco 007 - http://wetheadmedia.com/taco-007-circulator-pump/

4. ECE 4760 course website - http://instruct1.cit.cornell.edu/courses/ee476/

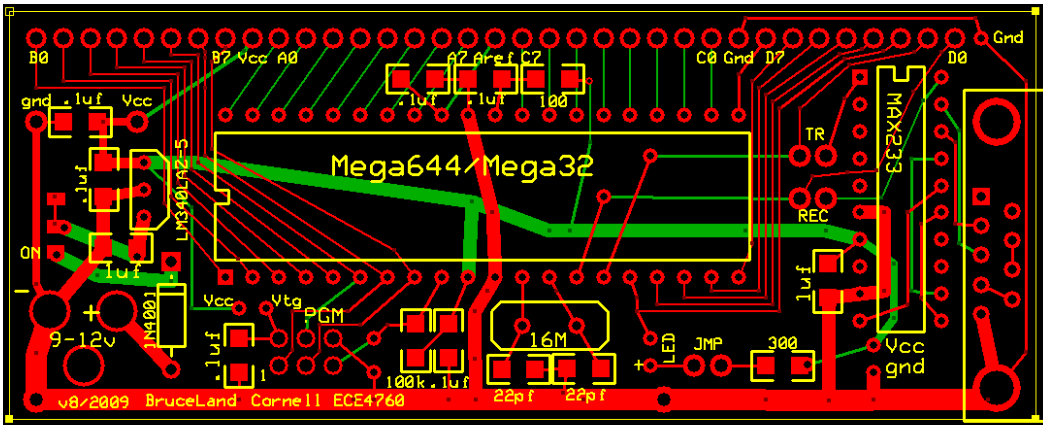
5. AVR Libc - http://www.nongnu.org/avr-libc/

6. Cornell University Solar Decathlon: Alternative System Project Manual

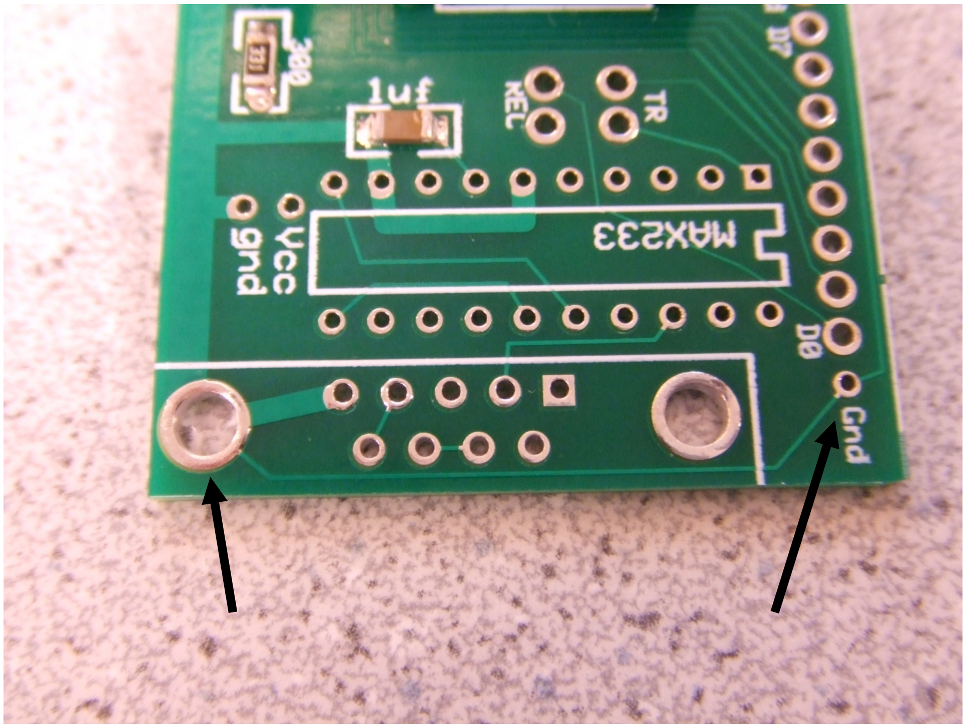
8. Appendix

Hardware schematics and pictures

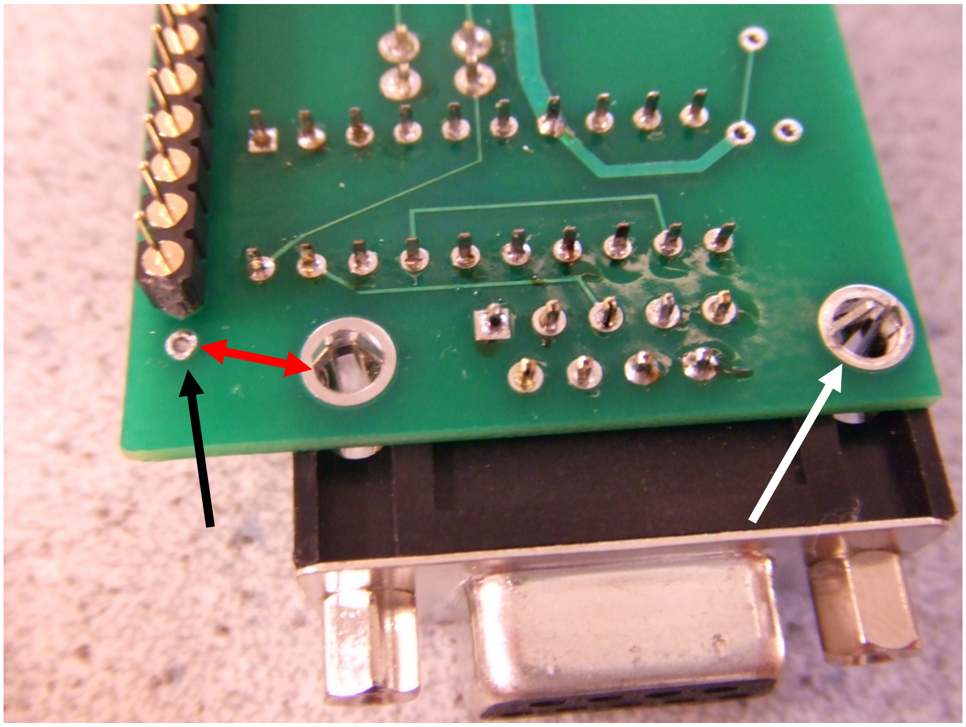
Prototype board schematics



Prototype board ground connection diagram 1

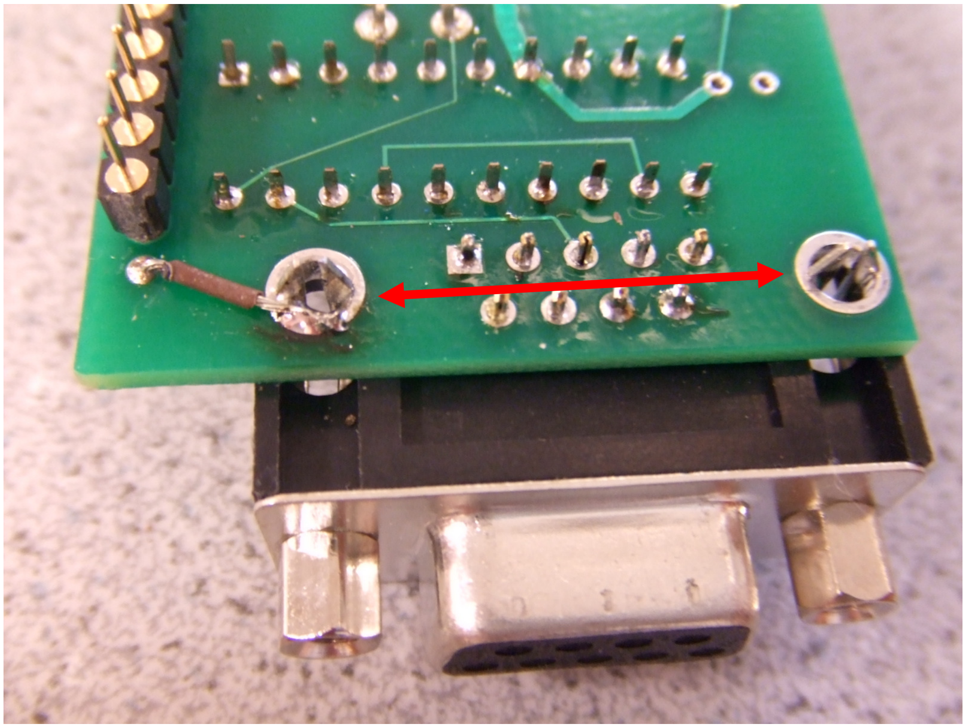


Prototype board ground connection diagram 2



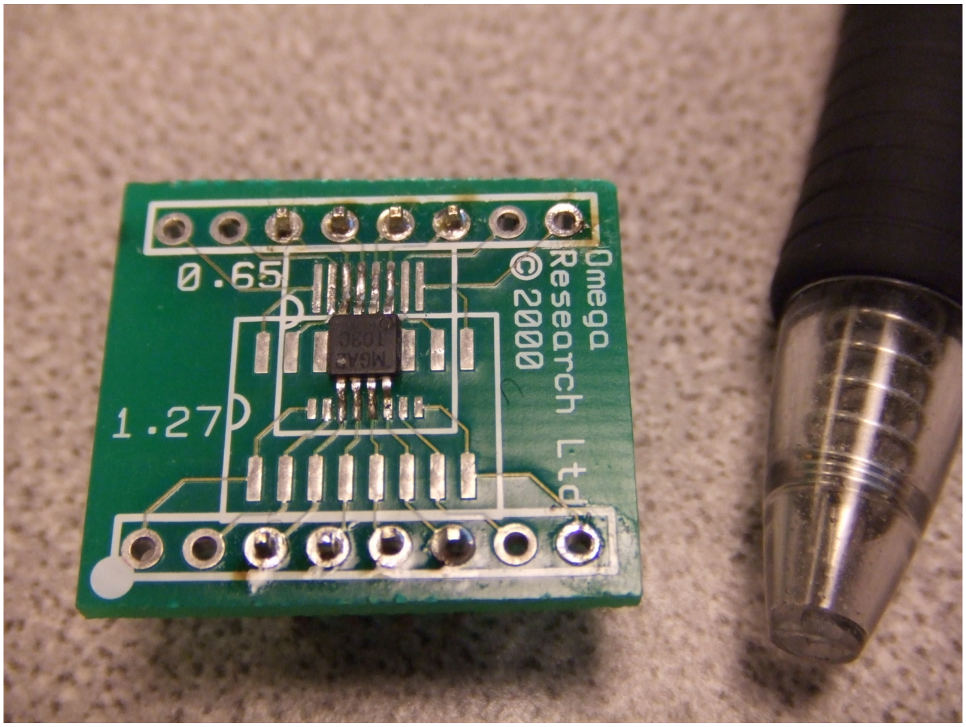
The printed connection between of two holes was broken during the soldering procedure. Therefore I had to set up the connection with wire.

Prototype board ground connection diagram 3

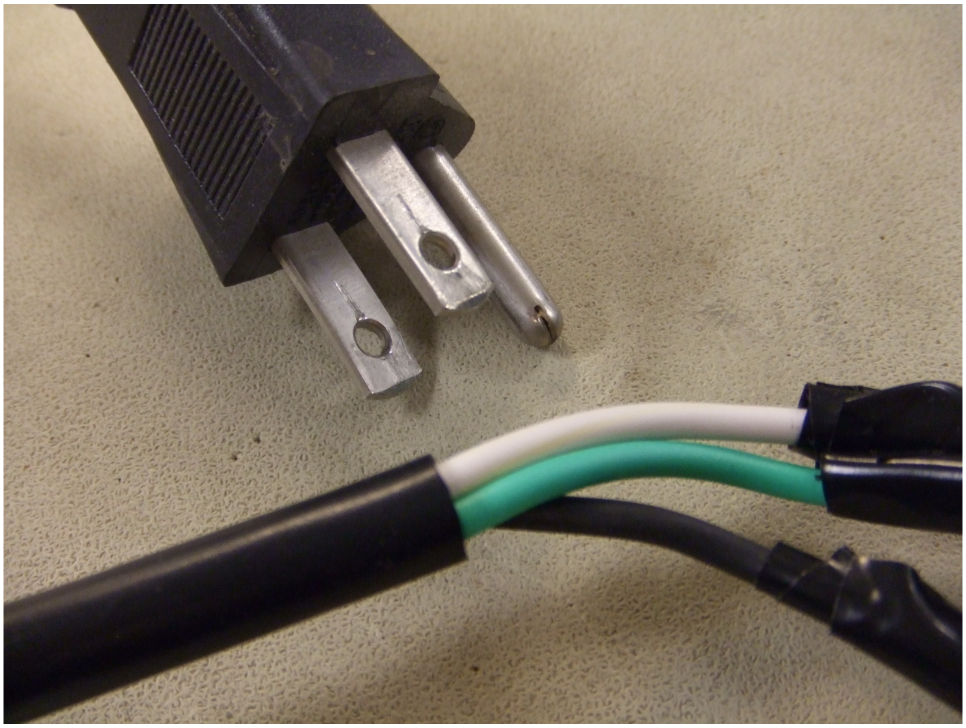


The two large holes were connected via the body of the D-sub connector.

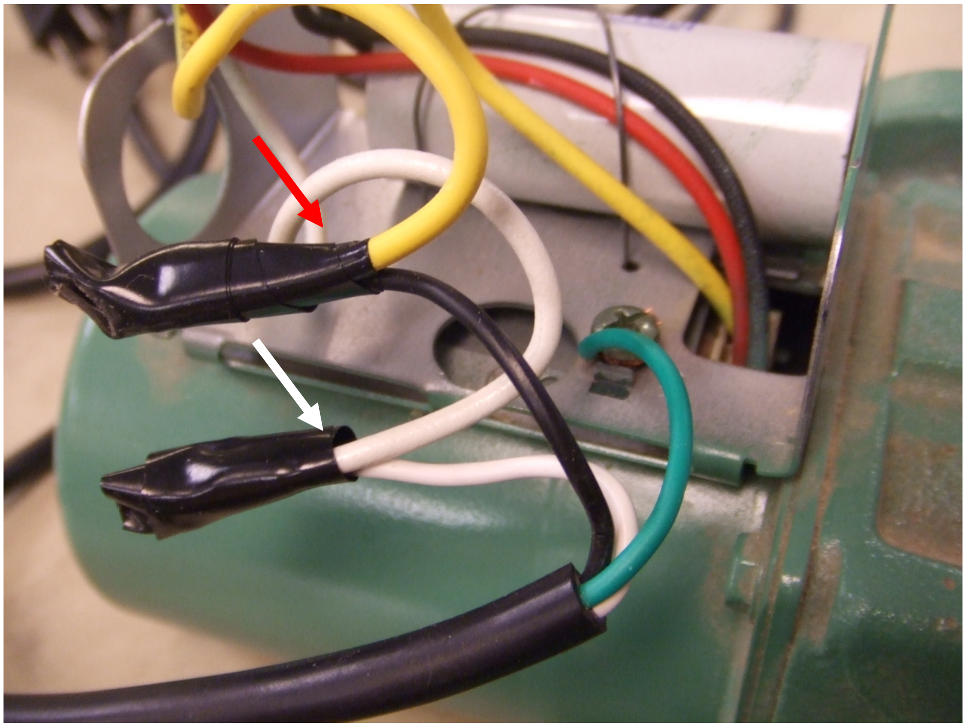
Temperature sensor LM70 on the breakout board



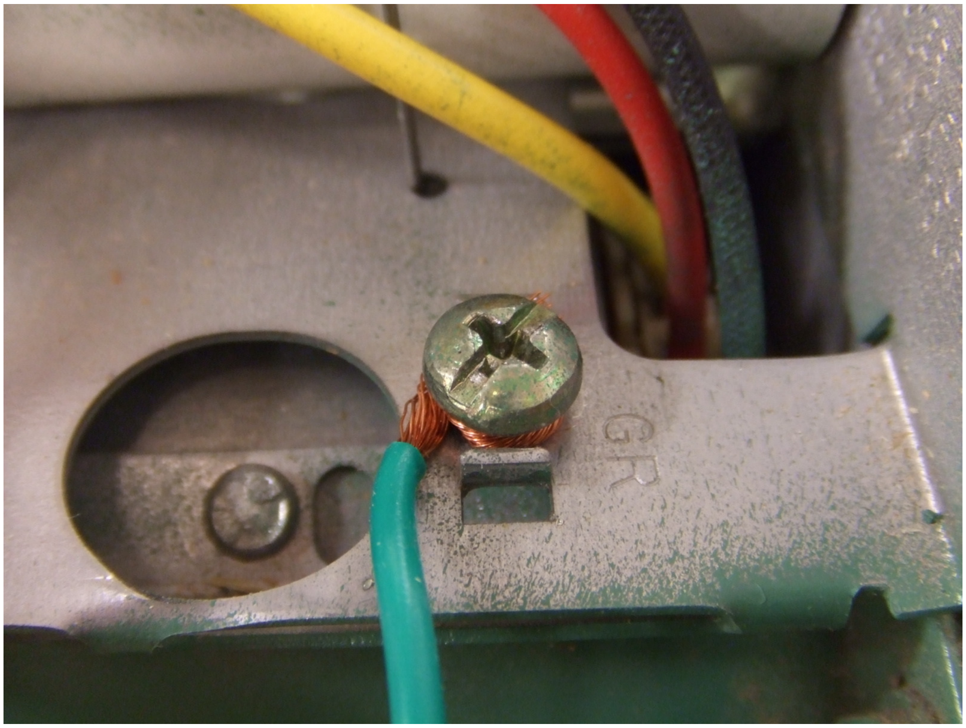
Stripped power cable with 3 wires (hot, neutral and ground)



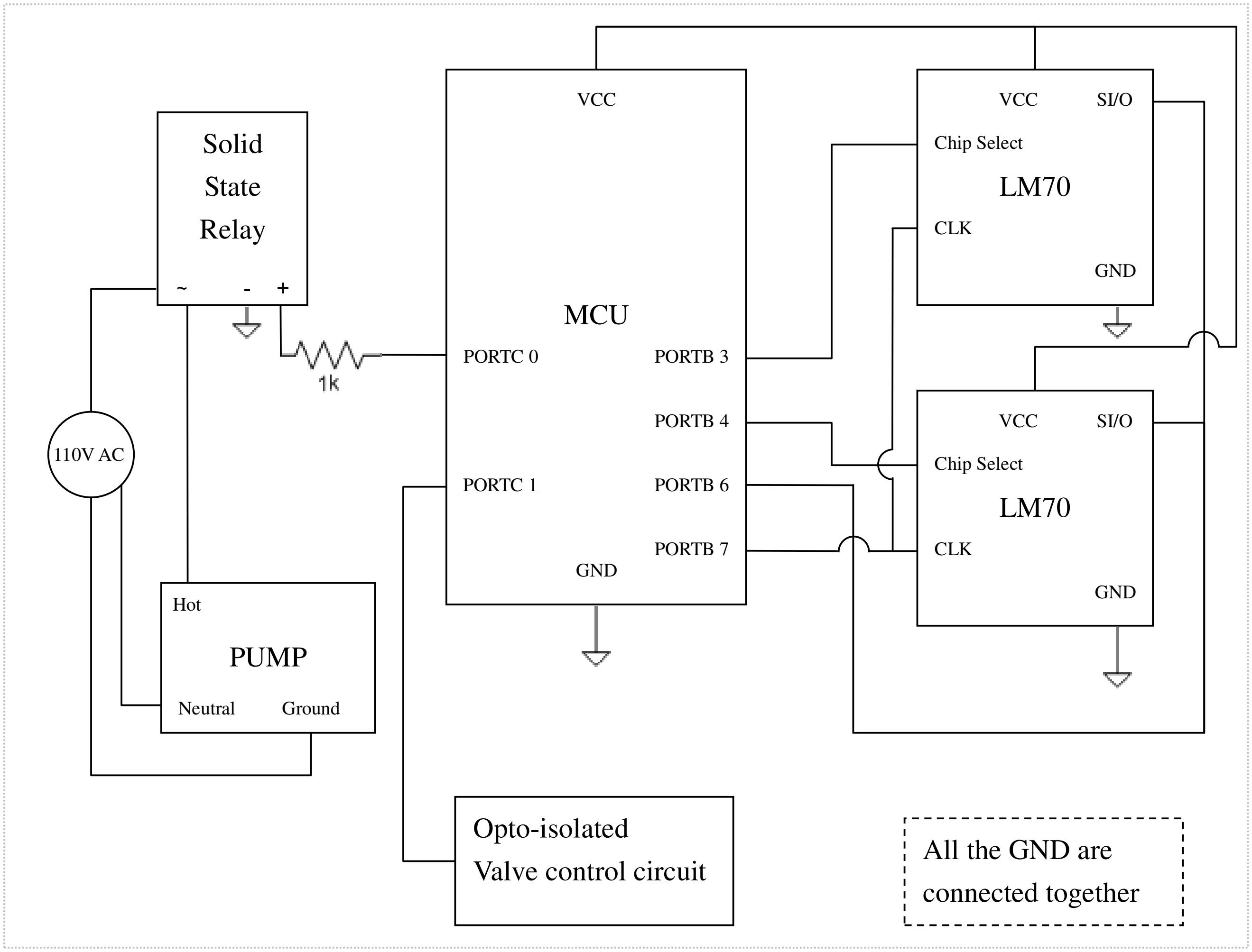
Soldered wires from the power cord to the pump



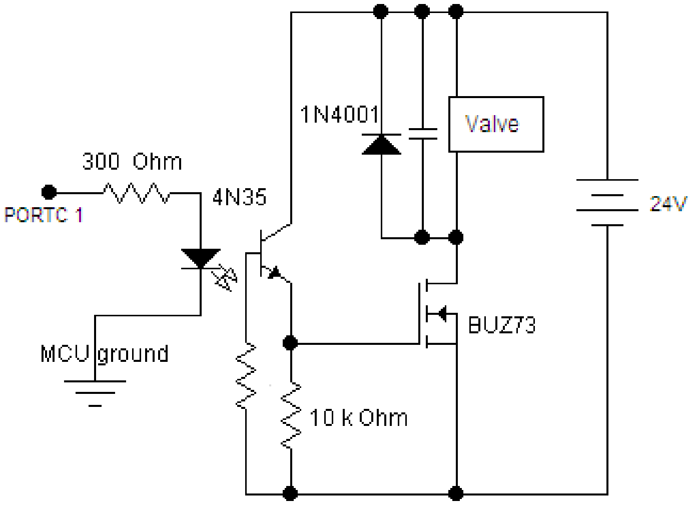
Ground connection to the pump body



Control System schematics

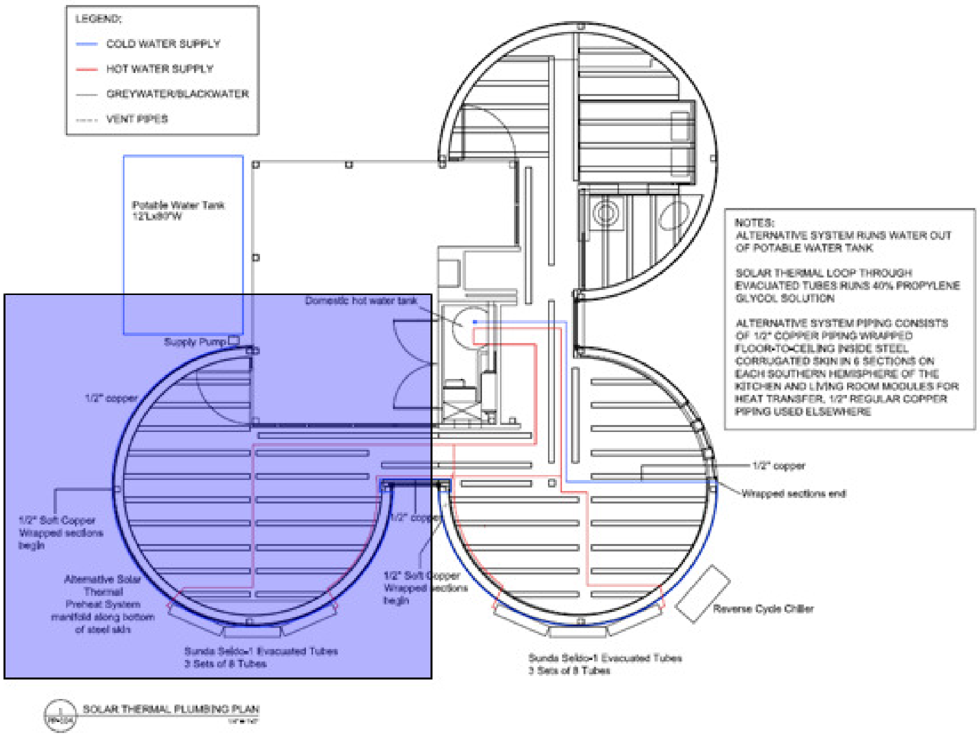


Valve control circuit schematics (Modified from ECE 4760 Lab 5)



Solar thermal plumbing layout

Solar Thermal Plumbing Diagram
(Adopted from solar thermal sub-team document)


LEGEND:
COLD WATER SUPPLY
HOT WATER SUPPLY
GREYWATER/BLACKWATER
VENT PIPES
Potable Water Tank 12'Lx80"W
Domestic hot water tank
Supply Pump
1/2" copper
1/2" Soft Copper Wrapped sections begin
Alternative Solar Thermal Preheat System manifold along bottom of steel skin
Sunda Seido-1 Evacuated Tubes 3 Sets of 8 Tubes
1/2" copper
1/2" Soft Copper Wrapped sections begin
Sunda Seido-1 Evacuated Tubes 3 Sets of 8 Tubes
Reverse Cycle Chiller
1/2" copper
Wrapped sections end
SOLAR THERMAL PLUMBING PLAN
1/4" = 1'-0"

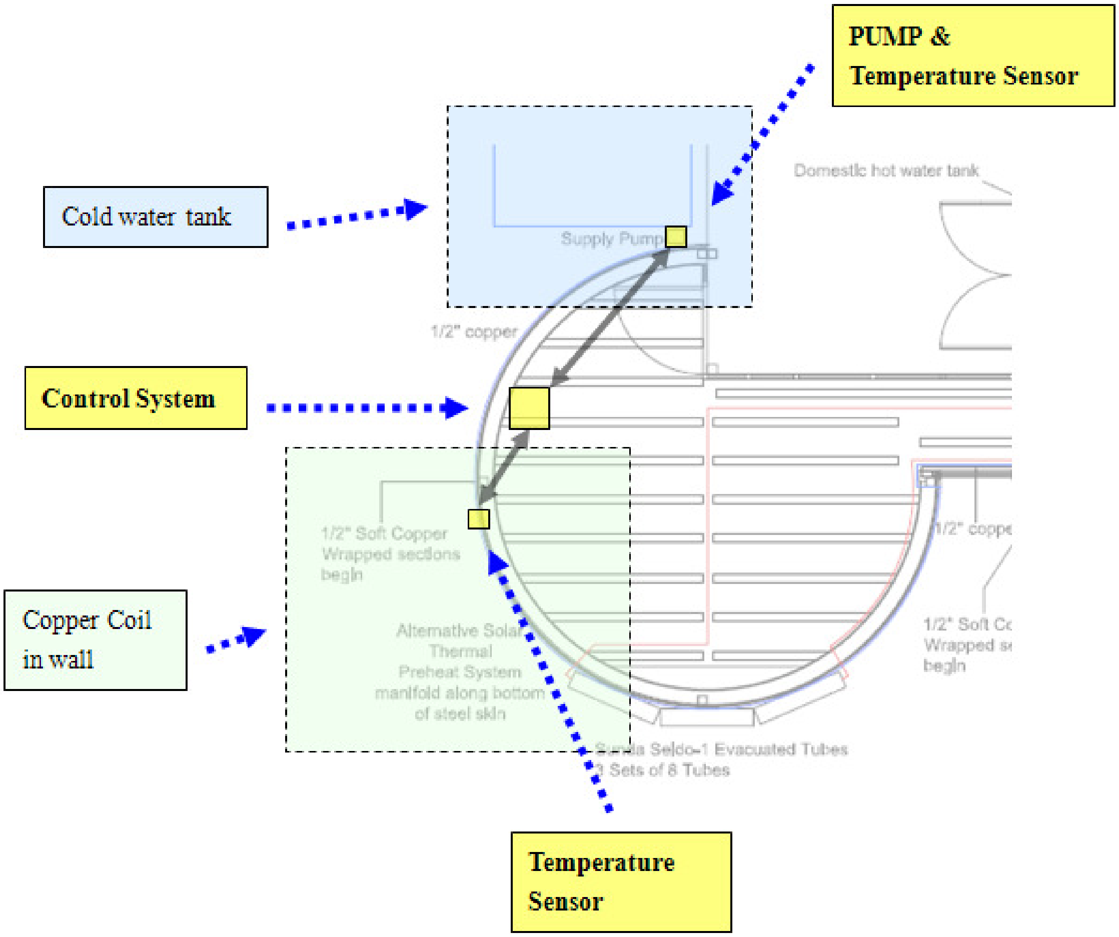
NOTES:
ALTERNATIVE SYSTEM RUNS WATER OUT OF POTABLE WATER TANK

SOLAR THERMAL LOOP THROUGH EVACUATED TUBES RUNS 40% PROPYLENE GLYCOL SOLUTION

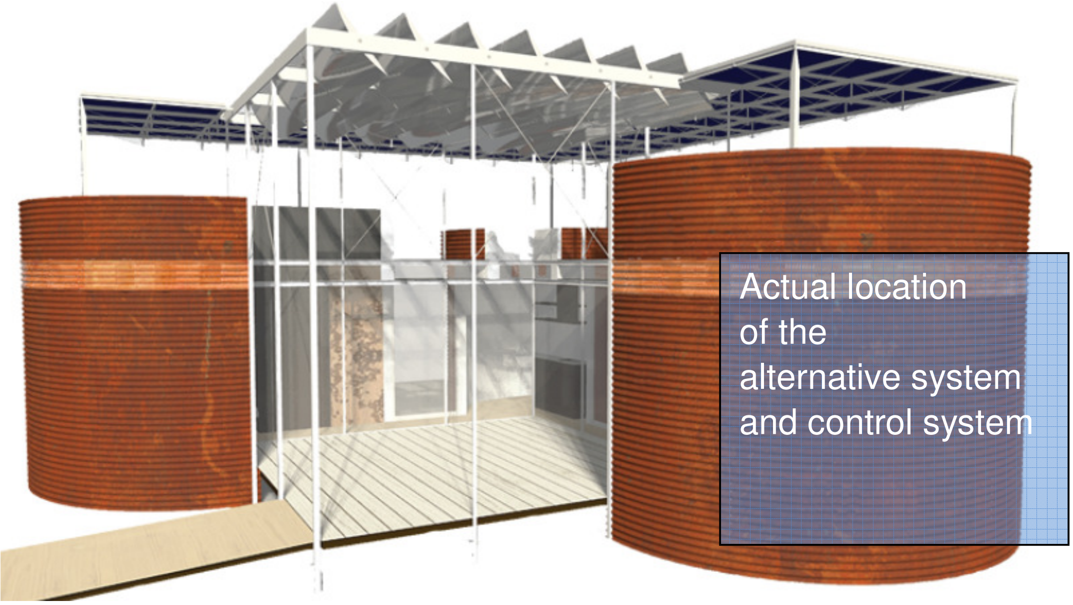
ALTERNATIVE SYSTEM PIPING CONSISTS OF 1/2" COPPER PIPING WRAPPED FLOOR-TO-CEILING INSIDE STEEL CORRUGATED SKIN IN 6 SECTIONS ON EACH SOUTHERN HEMISPHERE OF THE KITCHEN AND LIVING ROOM MODULES FOR HEAT TRANSFER, 1/2" REGULAR COPPER PIPING USED ELSEWHERE

The alternative system is located at the southwest side.

Enlarged Southwest side of the house layout



3D rendition of the CUSD House



Code Listing

```
// Cornell University Department of Electrical Engineering
// Master of Engineering (Electrical) Design Project
// Wei-jiunn Jang
// AVRStudio / ATmega644

#include <inttypes.h>
#include <avr/io.h>
#include <avr/interrupt.h>
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

//set up the debugging utility ASSERT
#define __ASSERT_USE_STDERR
#include <assert.h>
#include "uart.h"
// UART file descriptor
// putchar and getchar are in uart.c
FILE uart_str = FDEV_SETUP_STREAM(uart_putchar, uart_getchar,
_FDEV_SETUP_RW);


unsigned char enter_pressed;


//timeout values for each task
#define t1 100
#define t2 100



//menu state machine state names
#define main_menu 1
#define choose_sensor 2
#define set_threshold 21
#define control_pump 22
#define release_pump 23
```

```
#define celsius 4
#define fahrenheit 5



#define begin {
#define end   }

//the  subroutines
void task1(void);
void task2(void);
void getstr_int(void);  // Starts getting a string from serial line
void putstr_int(void);  // Starts a send to serial line
void initialize(void);  // All the usual mcu stuff

volatile int time1, time2;      // task scheduling timeout counters
char v[10];
char newstr ;

// when code added is invalid, set flag;
unsigned char invalid;



// for loop index
unsigned char i;

// RXC ISR variables
volatile unsigned char r_index;  //current string index
volatile char r_buffer[16]; //input string
volatile char r_ready;  //flag for receive done
volatile char r_char;  //current character

// TX ISR variables
volatile unsigned char t_index;  //current string index
volatile char t_buffer[300];    //output string
volatile char t_ready;  //flag for transmit done
volatile char t_char;  //current character
```

```
// toggling LED variable
unsigned char LED;

// variables for main fuctions
unsigned char display_menu;
unsigned char MENU;



//display TIME and MENU subroutines
void show_menu(void);

// bit handling macros for i/o registers
#define READ(U, N) ((U) >> (N) & 1u)
#define SET(U, N) ((void)((U) |= 1u << (N)))
#define CLR(U, N) ((void)((U) &= ~(1u << (N))))
#define FLIP(U, N) ((void)((U) ^= 1u << (N)))

char Hbits, Lbits;
double temp[2];
int threshold;
char debug_led;
char status = 0;
char valve[4];
char force_status[4];

char force = 0;


// Celsius mode(0) or Fahrenheit(1)
char degree = 0;

#define set_temp 1
#define control 2
#define release 3
```

```
//*******************************************************
//timer 0 overflow ISR
ISR (TIMER0_COMPA_vect)
begin
    //Decrement the times if they are not already zero
    if (time1>0)    --time1;
    if (time2>0)    --time2;
end

//*******************************************************
// UART character-ready ISR
// builds a sting and signals when the string is complete
// supports backspace

ISR (USART0_RX_vect)
begin
    r_char = UDR0 ;    //get a char

    //build the input string
    if (r_char != '\r') // Is the input a <enter>?
    begin
        if (r_char == '\b') // Is the input a backspace?
        begin
            if (r_index > 0)
            begin
                putchar('\b');  // backup
                putchar(' ');   // erase the character on the screen
                putchar('\b');  // backup
                --r_index ;     // wipe a character from the string
            end
        end
        else if (r_char == 27)
        begin
```

```
            MENU = main_menu;
            display_menu = 0;
            putchar(12);
        end
        else if (r_char == ' ');    // ignore all the space
        else
        begin
            UDR0 = r_char;
            r_buffer[r_index++] = r_char ; // add a character to the string
        end
    end
    else                    // Human pressed <enter>
    begin
        putchar('\n');          //use putchar to avoid overwrite
        r_buffer[r_index] = 0x00;   //zero terminate
        r_ready = 1;                //signal cmd processor
        UCSR0B ^= (1<<RXCIE0) ;     //stop rec ISR -- clear rxc
    end
end

/********************************************************/
//UART xmit-empty ISR
ISR (USART0_UDRE_vect)
begin
    t_char = t_buffer[++t_index];
    if (t_char == 0)            // end of string?
    begin
        UCSR0B ^= (1<<UDRIE0) ; // kill isr -- clear tx enable
        t_ready = 1;            // transmit done
    end
    else    UDR0 = t_char ;     //send the char
end

//**********************************************************
//Entry point and task scheduler loop
int main(void)
begin
    initialize();
    while(1)
    begin
        if (time1==0){time1=t1; task1(); }
        if (time2==0){time2=t2; task2(); }
    end
end



//************************************************************
//Task 1   input a string and print it
void task1(void)
begin
  //print ad get another serial string
  if (r_ready)
  begin
    enter_pressed = 1;
    // read string which is now ready
    sscanf(r_buffer,"%s",v);
    if (r_buffer[0] == 0) v[0] = 0;

    // set up procedure to get the next string input
    // and read it using receive ISR
    getstr_int();
  end
end

//************************************************************
//Task 2  print the meaasge and system time in seconds
void task2(void)
begin

    // update sensor value
    debug_led = debug_led ^ 1;  // blink LED on the prototype board
(PORTD.2)
    PORTD = (debug_led<<2);
    for(int i=0;i<2;i++)
    begin
        CLR(PORTB,i+3);     //chip select low begins transmission
        // send signal to get High byte
        SPDR = 0;
        //wait until SPIF is set (SPI done)
        while (!(SPSR & (1<<SPIF)));
        Hbits = SPDR;       // get back Hbits

        // send signal to get Low byte
        SPDR = 0;
        //wait until SPIF is set (SPI done)
        while (!(SPSR & (1<<SPIF)));
        Lbits = SPDR;       // get back Lbits
        SET(PORTB,i+3);     //chip select high ends transmission

        // calculate the temperature
        temp[i] = (double)Hbits * 2;
        temp[i] = temp[i] + ((double)(Lbits >> 5))/4;


        if (force == 0)     // only change status when there's no force
on/off
        begin
            if (temp[0] >= threshold)
            begin
                status = 1;
                valve[0] = 'O';
                valve[1] = 'n';
                valve[2] = ' ';
            end
            else if (temp[0] < temp[1]+2)
            begin
                status = 0;
                valve[0] = 'O';
                valve[1] = 'f';
                valve[2] = 'f';
            end
        end

        if (status == 1)
            PORTC = 0x01;
        else
            PORTC = 0;

    end


    switch (MENU)
    begin

    case main_menu:
        if (enter_pressed == 0)     // when enter is not pressed
        begin
            if (display_menu == 0)
            begin
                putchar(12);
                show_menu();
                display_menu = 1;
            end
            MENU = main_menu;
        end
        else                        // when enter is pressed
        begin
            if (strlen(v) == 1)
            begin                       // check what was entered

                if (v[0] == '1')
                begin
                    if (!degree) fprintf(stdout,"Please enter threshold
temperature (30 C - 99 C) >>");
                    else fprintf(stdout,"Please enter threshold
temperature (86 F - 210 F) >>");
                    MENU = set_threshold;
                    enter_pressed = 0;
                end
                else if (v[0] == '2')
                begin
                    fprintf(stdout,"Turn On/Off pump? (1/0) >>");
                    MENU = control_pump;
                    enter_pressed = 0;
                end

                else if (v[0] == '3')
                begin
                    fprintf(stdout,"Release control over pump? (y/n)
>>");
                    MENU = release_pump;
                    enter_pressed = 0;
                end

                else if (v[0] == '4')       // change to celsius mode
                begin
                    degree = 0;
                    MENU = main_menu;
                    display_menu = 0;
                    enter_pressed = 0;
                end

                else if (v[0] == '5')       // change to fahrenheit
mode
                begin
                    degree = 1;
                    MENU = main_menu;
                    display_menu = 0;
                    enter_pressed = 0;
                end
                else
                begin
                    fprintf(stdout, "invalid entry.\n\r");
                    enter_pressed = 0;
                end
            end
            else
            begin
                fprintf(stdout, "invalid entry.\n\r");
                enter_pressed = 0;
            end
        end
        break;


    case set_threshold:
        if (enter_pressed == 1)
        begin
            // when addind a code, first check whether the length is 4
            if (strlen(v) == 2 || strlen(v) == 3)
            begin
                if (!degree)
                begin
                    if (atoi(v) >= 30 && atoi(v) <= 99)
                    begin
                        for(i=0;i<strlen(v);i++)
                        begin           // then check whether they are
all numbers
                            if(v[i]<48 || v[i]>57 ) invalid = 1;
                            else invalid = 0;
                        end
                    end
                    else invalid = 1;
                end
                else
                begin
                    if (atoi(v) >= 86 && atoi(v) <= 210)
                    begin
                        for(i=0;i<strlen(v);i++)
                        begin           // then check whether they are
all numbers
                            if(v[i]<48 || v[i]>57 ) invalid = 1;
                            else invalid = 0;
                        end
                    end
                    else invalid = 1;
                end

                if (invalid == 0)
                begin
                    if (!degree) threshold = atoi(v);
                    else threshold = ((atoi(v))- 32) * 5 / 9;

                    enter_pressed = 0;
                    display_menu = 0;
                    MENU = main_menu;
                end
                else
                begin
                    invalid = 0;
                    if (!degree) fprintf(stdout,"invalid
entry.\n\rPlease enter threshold temperature (30 C - 99 C) >>");
                    else fprintf(stdout,"invalid entry.\n\rPlease
enter threshold temperature (86 F - 210 F) >>");
                end
            end
            else
            begin
                if (!degree) fprintf(stdout,"invalid entry.\n\rPlease
enter threshold temperature (30 C - 99 C) >>");
                else fprintf(stdout,"invalid entry.\n\rPlease enter
threshold temperature (86 F - 210 F) >>");
            end
            enter_pressed = 0;
        end
        else
            MENU = set_threshold;
        break;

    case control_pump:
        if (enter_pressed == 1)
        begin
```

```
            // when choosing sensor, should be 1 or 2
            if (strlen(v) == 1)
            begin
                if (v[0]==48)   //off
                begin
                    MENU = main_menu;
                    display_menu = 0;
                    status = 0;
                    valve[0] = 'O';
                    valve[1] = 'f';
                    valve[2] = 'f';
                    force = 1;
                    force_status[0] = 'Y';
                    force_status[1] = 'e';
                    force_status[2] = 's';
                end
                else if (v[0]==49)  //on
                begin
                    MENU = main_menu;
                    display_menu = 0;
                    status = 1;
                    valve[0] = 'O';
                    valve[1] = 'n';
                    valve[2] = ' ';
                    force = 1;
                    force_status[0] = 'Y';
                    force_status[1] = 'e';
                    force_status[2] = 's';
                end
                else
                fprintf(stdout, "invalid entry\n\rTurn On/Off Pump?
(1/0)");
            end
            else
                fprintf(stdout, "invalid entry\n\rTurn On/Off Pump?
(1/0)");
            enter_pressed = 0;
        end
        else
            MENU = control_pump;
        break;

    case release_pump:
        if (enter_pressed == 1)
        begin
            // when choosing sensor, should be 1 or 2
            if (strlen(v) == 1)
            begin
                if (v[0] == 121)    //yes
                begin
                    MENU = main_menu;
                    display_menu = 0;
                    force = 0;
                    force_status[0] = ' ';
                    force_status[1] = ' ';
                    force_status[2] = ' ';
                end
                else if (v[0] == 110)   //on
                begin
                    MENU = main_menu;
                    display_menu = 0;
                end
                else
                fprintf(stdout, "invalid entry\n\rRelease control over
pump? (y/n)\n\r>>");
            end
            else
                fprintf(stdout, "invalid entry\n\rRelease control over
pump? (y/n)\n\r>>");

            enter_pressed = 0;
        end
        else
            MENU = release_pump;
        break;
    end
```

```
end



//***********************************************************
// Non-blocking keyboard input: initializes ISR-driven receive.
// This routine merely sets up the ISR, which then
//does all the work of getting a command.
void getstr_int(void)
begin
    r_ready=0;  // mark string as not ready
    r_index=0;  // reset index
    // turn on receive ISR
    UCSR0B |= (1<<RXCIE0) ;
end

//***********************************************************
// Nonblocking print: initializes ISR-driven transmit.
// This routine merely sets up the ISR, then
// sends one character, The ISR does all the work.
void putstr_int(void)
begin
    t_ready=0;  // mark transmitter as busy
    t_index=0;  // reset index
    // see if there is actually a string
    if (t_buffer[0]>0)
    begin
        // if so, send the first chararcter
        putchar(t_buffer[0]);
        // and turn on transmit (UDR empty) ISR
        UCSR0B |= (1<<UDRIE0) ;
    end
end


void show_menu(void)
begin
    fprintf(stdout, "------ Cornell University  Solar Decathlon
------\n\r");
    fprintf(stdout, "--- Solar Hot Water Collecting Control System
---\n\r");
    fprintf(stdout,
"--------------------------------------------------\n\r");
    fprintf(stdout, "--| Sensor     |-|   Coil    |-|  WaterTank
|--\n\r");

    if (!degree)
    fprintf(stdout, "--| Temperature |-| %7.2f C  |-| %7.2f C
|--\n\r",temp[0],temp[1]);
    else
    fprintf(stdout, "--| Temperature |-| %7.2f F  |-| %7.2f F
|--\n\r",temp[0]*1.8+32,temp[1]*1.8+32);
    if (!degree)
    fprintf(stdout, "--| Threshold   |-| %4d   C  |-| %7.2f C
|--\n\r",threshold,temp[1]+2);
    else
        begin
        if( ((double)threshold*1.8+32) - (char)(threshold*1.8+32) > 0)
    fprintf(stdout, "--| Threshold   |-| %4d   F  |-| %7.2f F
|--\n\r",(char)(threshold*1.8+32)+1,(temp[1]+2)*1.8+32);
        else
    fprintf(stdout, "--| Threshold   |-| %4d   F  |-| %7.2f F
|--\n\r",(char)(threshold*1.8+32),(temp[1]+2)*1.8+32);
        end

    fprintf(stdout, "--| Pump Status |-|    %3s   |-|\n\r",valve);
    fprintf(stdout, "--| Controlled? |-|    %3s
|-|\n\r",force_status);
    fprintf(stdout,
"--------------------------------------------------\n\r");




    sprintf(t_buffer, "1. Set threshold temperature\n\r2. Manual control
\n\r3. Release control\n\r4. Switch to Celsius\n\r5. Switch to
Fahrenheit\n\r-------------------------------------------------\n\r>>
");

    newstr = 1;

    if (t_ready && newstr)
    begin
        // make a string of system time (sec) and number from task 1
        //sprintf(t_buffer,"%ld %d\n\r",time/1000, v) ;

        // print it using transmit ISR
        putstr_int();
        // clear the string ready handshake from task 1
        newstr = 0;
    end
end




//**********************************************************
//Set it all up
void initialize(void)
begin

    // init the UART -- uart_init() is in uart.c
    uart_init();
    stdout = stdin = stderr = &uart_str;
    fprintf(stdout,"Starting ISR UART demo...\n\r");
    putchar(12);

    // set up timer 0
    OCR0A = 249;                // clear after 250 counts
    TIMSK0 = (1<<OCIE0A) ;  //turn on timer 0 cmp-match ISR

    // turn on timer 0 clear on match
    TCCR0A = (1<<WGM01) ;
```

```
// timer 0 prescalar to 64
TCCR0B = 3 ;

// init the task timers
time1=t1;
time2=t2;

// initialize the USRT handshake flags
r_ready=0; // initially, there is no input ready
t_ready=1; // initially, the transmitter is ready

// initialize main function variables
display_menu = 0;
MENU = main_menu;
enter_pressed = 0;
invalid = 0;

strcpy(force_status, "   ");
strcpy(valve, "Off");

// output pin to pump controlling relay
DDRC = 0x01;
PORTC = 0;
// output pin debug_led
DDRD |= (1<<2) ; // LEDs
debug_led = 0x00;
// LM70 reading
//set up i/o data direction
//DDRB.4 = 1; //output chip select for DAC (notSYNC)
//DDRB.5 = 1; //output MOSI to ADC
//DDRB.6 = 0; //input MISO from ADC
//DDRB.7 = 1; //output SCLK
DDRB = (1<<DDB3) | (1<<DDB4) | (1<<DDB5) | (1<<DDB7) ;
// initialize notSYNC
SET(PORTB,4);
SET(PORTB,3);

//set up SPI
```

```
    //bit 7 SPIE=0 no ISR
    //bit 6 SPE=1 enable spi
    //bit 5 DORD=0 msb first
    //bit 4 MSTR=1 Mega32 is spi master
    //bit 3 CPOL=1 clock polarity
    //bit 2 CPHA=1 clock phase
    //bit 1,0 rate sel=10 along with SPRC=1 sets clk to f/32 = 500 kHz
    SPCR = (1<<SPE) | (1<<MSTR) | (1<<CPOL) | (1<<CPHA) | (1<<SPR1) ;
//SPCR SPCR = 0b01011110 ;
    SPSR = (1<<SPI2X) ; //SPSR = 1;

    // initialize threshold temperature to 50C
    threshold = 50;

    // turn in ISRs
    // but note that UART ISRs are enabled when reading/writing
    sei();
    // start waiting for input
    getstr_int();
end
```