POWERING YOUR WATER HEATER USING SOLAR ENERGY

An Undergraduate Research Scholars Thesis

by

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Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
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May 2013

Major: Electrical Engineering

Applied Mathematical Science

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ABSTRACT

POWERING YOUR WATER HEATER USING SOLAR ENERGY. (May 2013)

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This report is a detailed overview of my research on solar water heating. Solar water heaters may be used to either supplement or even replace a standard water heater. In addition to being environmentally friendly, solar heaters can save a homeowner hundreds of dollars per year in electricity bills. Because all of the energy remains as heat, water heaters can achieve much higher efficiencies than photovoltaic solar panels. The objective of my research was to improve an existing solar water heater by optimizing its control system. I designed a circuit board to record temperature and flow rate data, and to control the system. In this circuit board I implemented a proportional control scheme designed to optimize the energy efficiency of the solar water heater. The circuit board also takes periodic temperature and flow rate measurements, and saves the results on a data server. I wrote a MATLAB script to parse and analyze the recorded data. My analysis showed that my control scheme performs much better than the previously used control method, particularly on colder days. The average increase in energy harvested by the system in a day was 3.22 kilowatt-hours. My research has shown the potential economic and environmental benefits of using a well-designed control system.

ACKNOWLEDGMENTS

I would like to thank Roy Miller for providing the initial water heating system and for funding this project. I would like to thank Dr. Jean Marie Linhart for providing invaluable advice throughout the course of the project, for teaching me about mathematical modeling, and for motivating this project. I would like to thank Dr. Elizabeth Tebeaux for helping with my research and literary review in the solar heating field. I would also like to thank Craig Ireton and Dylan McGarry for their assistance with the heat transfer modeling equations used in my data analysis.

NOMENCLATURE

CMP	Analog Comparator. Used to detect rising and falling edges generated by the flow meter.
HTF	Heat Transfer Fluid. Transfers energy from the roof solar collector to the hot water storage tank.
kB	Kilobyte. Unit used to refer to data quantities. Approximately 1000 bytes.
KWH	Kilowatt-Hours. Unit of energy.
LCD	Liquid Crystal Display.
mB	Megabyte. Unit used to refer to data quantities. Approximately 1,000,000 bytes.
MCU	Microcontroller. Standard Term.
NOAA	The United States National Oceanic and Atmospheric Administration.
PCB	Printed Circuit Board.
PID	Proportional-Integral-Derivative controller.
PWM	Pulse-Width Modulation. Used for proportional motor control.
RTC	Real-Time Clock. Digital timekeeper implemented in the microcontroller.
USB	Universal Serial Bus.

CHAPTER I

INTRODUCTION

Subject and Purpose of the Review

Solar water heating is an often-overlooked source of renewable energy. A properly designed solar water system can supplement or even replace a traditional electric or gas heater. Solar water heaters are environmentally friendly and can save a homeowner a great deal of money. However, the money saved by using a solar heater is proportional to the efficiency of that particular system.

Many different types of solar water heating systems exist. The type of system used often depends on the purpose and location. My research focuses on residential solar water heating systems in the U.S.

The purpose of my research is to develop an optimized solar water heating system. Once complete, this system will be easy to use, and will adapt to its environment autonomously. In order to maximize the energy gain of the system, I am utilizing anticipatory control methods based on weather forecasting and water usage prediction.

Rationale for the Topic

Solar water heating has become popular for two reasons. First, it saves money. Second, it saves the environment. Although the second idea may seem noble, saving money motivates most people. For this reason, I anticipate moving my project into the commercial product market once complete.

Solar water heating is not a new topic. However, most of the past research in the area has been focused in other countries, most notably China and Israel. In these countries, the focus is mass-producible passively controlled systems. Unfortunately, this trend has not yet caught on in the U.S.

Very few countries have such a glut of energy as the United States. Despite the North American wealth of natural resources and economic superiority, the price of energy constantly increases. This process makes renewable energy seem increasingly attractive. Solar water heating, a relatively simple option for American homeowners to go green, is much cheaper than photovoltaic solar panels and pays itself off more quickly.

System Description

The solar water heating system considered in my project is currently in use in my home in Austin, TX. This section explains the system; a diagram is given for reference in Figure I.1. A picture of the most important component of the system is shown in Figure I.2. These panels are collectively known as the solar collector, or simply as the collector. A heat transfer fluid (or HTF) is pumped through the collector, where it absorbs energy from the copper plates sitting under glass in the sunlight.

After it is heated, the HTF travels down an insulated pipe to a water storage tank (referred to as the solar tank). The pipe carrying the HTF coils around the exterior of the solar tank, and ascends back to the collector. This forms a closed loop system in which energy is transferred from the collector to the storage tank. The closed loop nature of the system

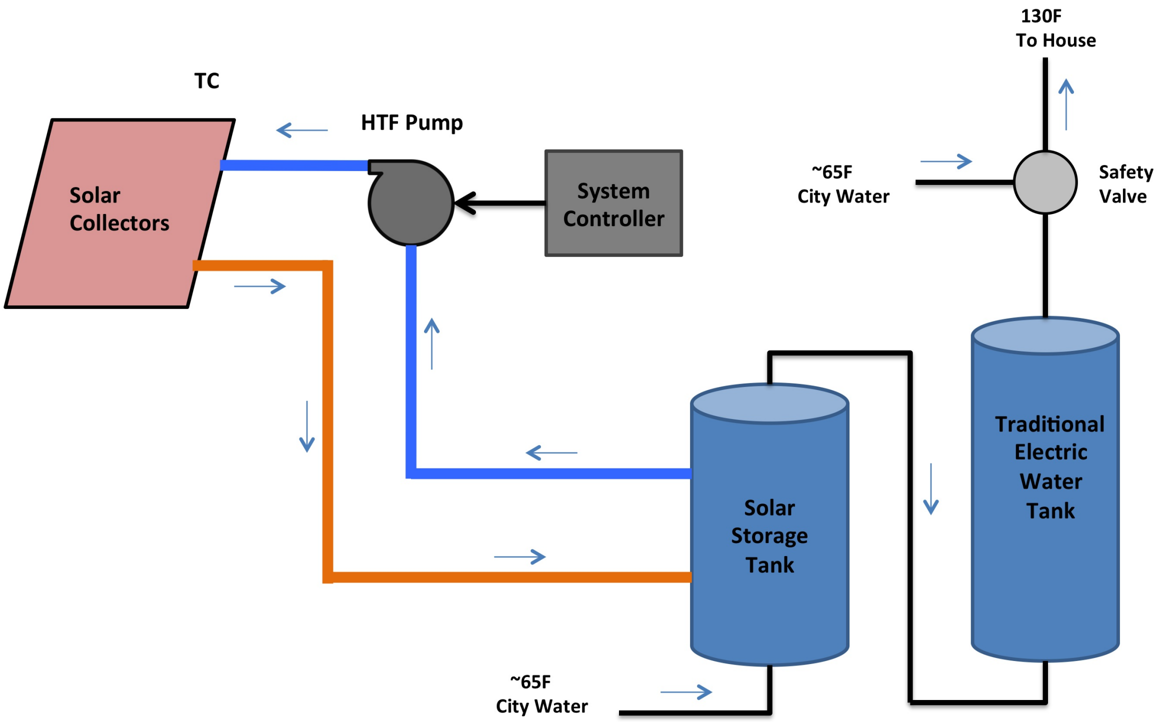

Fig. I.1. Diagram of the solar water heating system.

Fig. I.2. The solar collector panels.

means that the HTF does not directly interact with the water it heats. Because of this, we can use a mixture of Propylene Glycol (non-toxic antifreeze) and water for the heat transfer fluid and allow year-round operation of the system without risking freeze damage (i.e. burst pipes).

Water enters the base of the solar tank from the city main at roughly $65^o F$, depending on the ground temperature. This value is simply a rough average of gathered data. The HTF transfer coil heats the water in the solar tank. The heated water exits the tank, and is sent to a traditional hot water heater, where it is regulated to $130^o F$ (a standard temperature for residential water heaters) and distributed to the house as needed.

The described solar water heating system is what is known as an actively controlled system. This means that the flow rate of the HTF is controllable. My project focuses on the control of this flow rate, with the goal of optimizing the energy gathered. The system is monitored using digital thermometers and flow meters.

Goals of the Research

The primary goals of my research are as follows:

1. Develop an accurate, data-verified energy model of the solar water heating system.
2. Develop an optimized control scheme for the solar water heating system.

Methods

To achieve my first goal of modeling the energy in the system, I constructed a data logger and system control circuit board. This board periodically records system temperatures and flow rates at a variety of points within the system. This data is recorded once per minute, and is automatically uploaded to the Internet, where I can access it as desired. I have written a MATLAB script to analyze this data. I have used this script in conjunction with a theoretical energy model I previously developed to analyze the efficiency of the old control system. By simply comparing efficiencies, I will be able to objectively determine the benefit of my new control system.

For my second goal of creating an optimized control scheme, I am adapting my MATLAB script to allow for the simulation of various control schemes. Once I have used MATLAB to theoretically optimize the system control parameters, I will implement the control scheme in the physical system. This implementation also relies on the circuit board I designed. The board includes a Pulse Width Modulation (PWM) motor controller with a high-power H-bridge for proportional motor control of the Heat Transfer Fluid (HTF) pump.

CHAPTER II
METHODS

System Controller Design

Over the spring and summer of 2012, I designed a circuit board to monitor and control my solar water heating system. I initially specified the design requirements, the primary of which are listed below.

- Multi-temperature-sensor interface
- Flow meter interface
- Variable-speed DC motor controller
- PC communication interface
- On-board data storage

I next selected components capable of fulfilling the above requirements, and created the system schematic and layout. The full control board schematic, created using ORCAD is included in **Appendix A**. The layout, created using ExpressPCB is included in **Appendix B**. The control board is focused around a Silicon Laboratories 32-bit SiM3U167 microcontroller (MCU). Temperatures are recorded with Maxim digital thermometers, and flow rate is recorded by a Hall effect flow meter. The board includes a high-power H-bridge for motor control, an SD card for data storage, and a USB port for PC communication with a data server. A functional block diagram of the control board is included in Figure II.1.

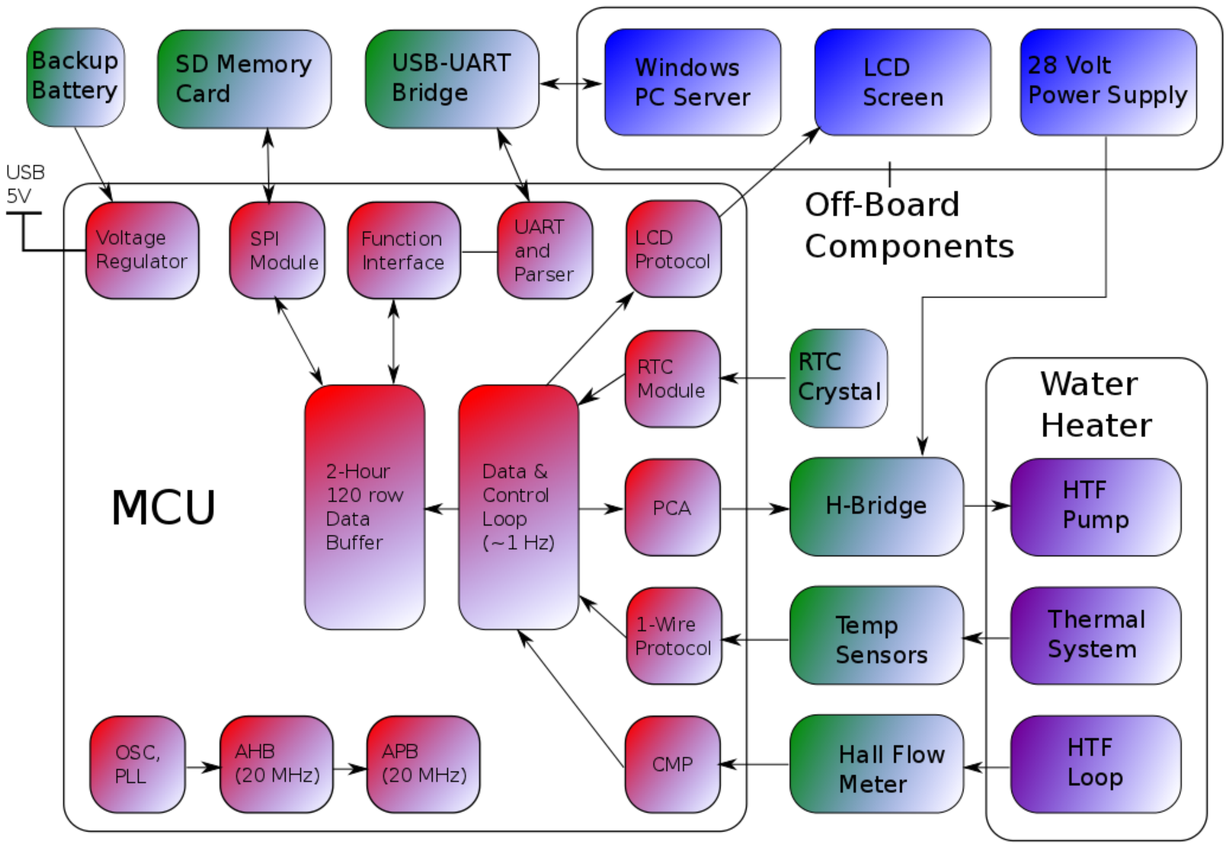

Fig. II.1. A functional block diagram of the solar water heating system control circuit board. Red blocks indicate code modules on the micro controller. Green blocks indicate components on the circuit board.

Data Collection

After completing the hardware design for the control system, I began the software design. This consisted of firmware written in Embedded C for the microcontroller on the board. The firmware was written to record 8 system temperatures, as well as hot water usage once per minute. The placements of the sensors are shown in Figure II.2. The flow meter following the electric water tank is a digital flow meter which generates a pulse every 0.1 gallons. This pulse is captured by the micro controller using a comparator interrupt. The flow meter on the heat transfer fluid loop is a mechanical meter with a visual readout. This meter was used to relate pump duty ratio to fluid flow rate.

This data is automatically recorded and uploaded to a PC data server via USB. This portion of the system was completed August 23, 2012, and has been recording system data nearly every day since. The system records roughly 100-120 kB of data per day, which works out to less than 400 mB of data per year. Data storage space is therefore not a concern. This data is uploaded to the server at 15-minute intervals, and concatenated into comma-seperated-value (.csv) files, with one file created and date-stamped per day. The data is extracted from these file at will by the MATLAB analysis script.

Data Analysis

I have written a MATLAB script to analyze the data gathered by the control board. This script has four primary purposes.

Energy Usage

First, the script determines the energy in the hot water used by the house. This is done by applying the thermodynamic equation $\dot{q} = \dot{m}C_p\Delta T$ to the system. C_p refers to the specific

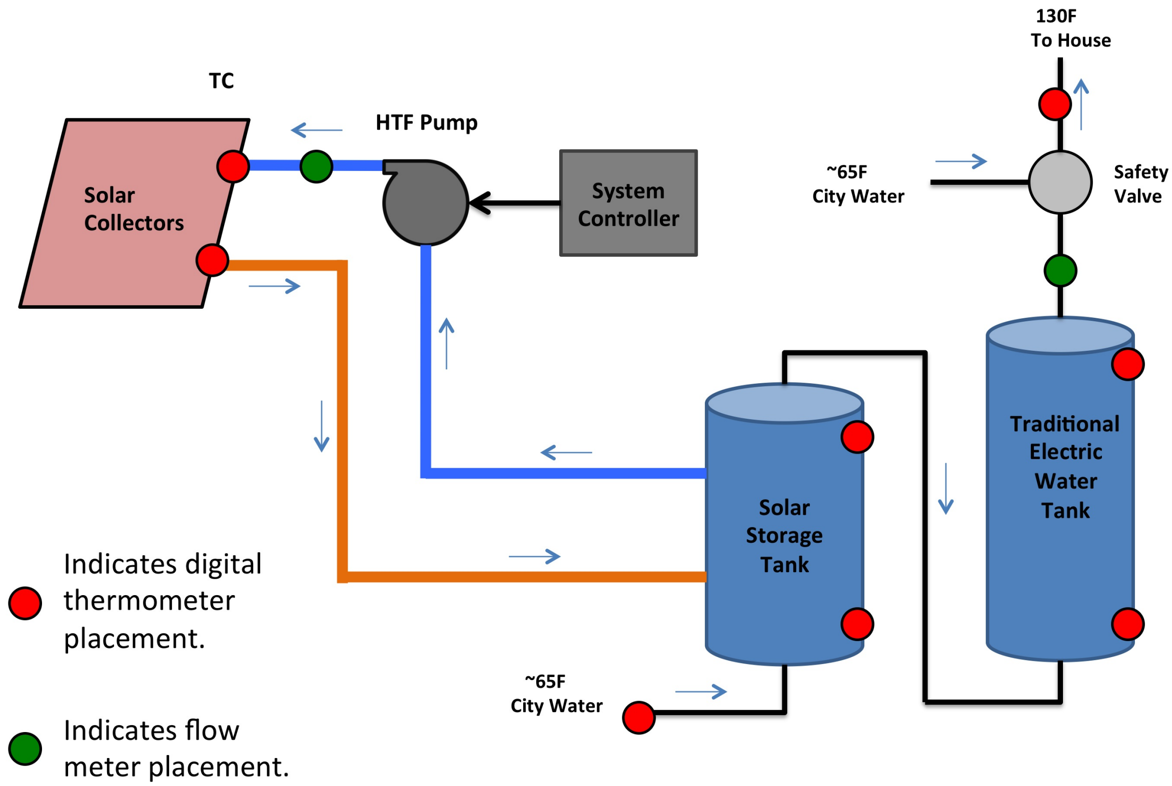

Fig. II.2. The placement of digital thermometers and flow meters within the system.

heat of water. ΔT is the temperature differential between the hot water going into the house, and the base water temperature of the water main. These temperatures are both recorded by the system. The mass flow rate ($\dot{m}$) of the water is determined by referring to the hot water flow counter recorded by the system. The 7-point difference method shown in Equation II.1 is used to estimate the mass flow rate to a low order of error.

$$f'(x) = -\frac{1}{60}f(x-3h)+\frac{3}{20}f(x-2h)-\frac{3}{4}f(x-h)+\frac{3}{4}f(x+h)-\frac{3}{20}f(x+2h)+\frac{1}{60}f(x+3h) \quad \text{(II.1)}$$

Daily Energy Gain

The second purpose of the MATLAB script is to determine the total energy harvested by the solar water heater in a given day. This is based on the energy in the solar storage tank at the beginning of the day (E_{initial}), the energy in the tank at the end of the day(E_{final}), and the energy extracted from the solar tank over the course of the day (E_{used}). This gain is computed using Equation II.2.

$$E_{\text{gain}} = \left(E_{\text{final}} - E_{\text{initial}}\right) + E_{\text{used}} \quad \text{(II.2)}$$

The solar tank energy delta is computed with Equation II.3, where m_{tank} is the mass of the water in the 80 gallon tank, C_p is the specific heat of water.

$$\left(E_{\text{final}} - E_{\text{initial}}\right) = m_{\text{tank}} C_p \left(T_{\text{final}} - T_{\text{initial}}\right) \quad \text{(II.3)}$$

T_{final} and T_{initial} are the average temperatures of the solar tank at the end and beginning of the day, assuming a linear temperature gradient with respect to height in the tank. They are computed using the temperature of the top of the solar tank (T_{top}) and the temperature of the bottom of the solar tank (T_{bottom}) by Equation II.4.

$$T_{\text{tank}} = \frac{1}{2}\left(T_{\text{top}} + T_{\text{bottom}}\right) \tag{II.4}$$

The energy extracted from the solar tank by the house (E_{used}) is computed by Equation II.5, where $\dot{m}$ is computed using Equation II.1.

$$E_{\text{used}} = \int \dot{m} C_p \left(T_{\text{tank}} - T_{\text{utility}}\right) dt \tag{II.5}$$

The total energy gain E_{gain} computed using Equation II.2 is then used as a metric to compare the effectiveness of control methods.

Daily Profiling

The third purpose of the MATLAB script is to develop a profiling scheme that organizes days into groups based on similar external conditions. Days in the same profile, but using different control schemes may be compared to determine which control scheme is more effective. I decided to use the following variables to set the profiles.

1. Level of cloud coverage (Clear, Few, Scattered, Broken, Overcast)

2. Average external temperature from 10am to 6pm, divided into 11 ranges.

Both of these records were obtained from NOAA, the National Oceanic and Atmospheric Administration.

Control System Simulation

Finally, the MATLAB script also determines the instantaneous power being harvested by the solar water system at any given time. This is easily analyzed by observing the temperature differential at the input and output of the solar collector. The flow rate of the heat transfer

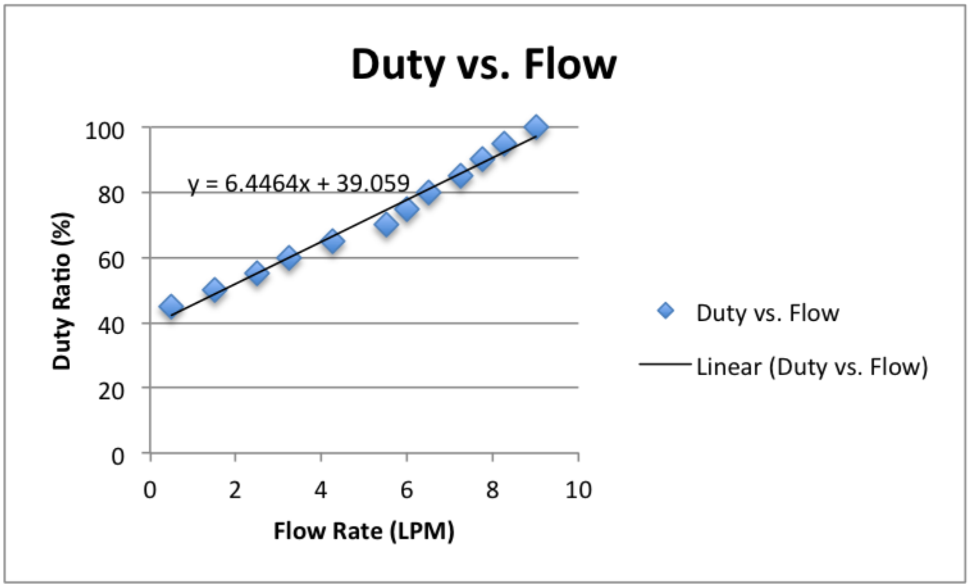

Fig. II.3. Recorded data of heat transfer fluid pump duty ratio versus flow rate.

fluid is proportional to the duty ratio set by the motor controller, as shown in Figure II.3. This relationship includes a negligible level of hysteresis. The data was recorded by gradually incrementing the pump duty ratio, and observing the change on the mechanical flow meter. The duty ratio was then gradually decremented to observe the effects of hysteresis on the flow rate.

The control board uses a simple control algorithm to set the pump duty ratio. This algorithm is replicated in MATLAB, and the linear function from Figure II.3 is applied to determine the transfer fluid flow rate ($\dot{m}$) using recorded data. Using temperatures recorded by the system, the equation $\dot{q} = \dot{m}C_p\Delta T$ is applied to find the thermal power into the system.

In this way, I can simulate the control system that was implemented in the system at the time the data was recorded. This retrospective view allows me to consider potential issues with the control method so I may fix them before they cause system damage.

Control System Optimization

Optimization through Simulation

The second purpose of the MATLAB script was to simulate the system and determine the effectiveness of various control schemes. In this way, I could test control methods and fine-tune control parameters without endangering the actual system components. In addition, simulation runs more quickly than direct testing. It is feasible to test large ranges of control parameters quickly, and simply choose the most effective. This can be easier than mathematically solving the system's modeling differential equations. Unfortunately, I did not have enough time to complete the system simulation. This would have required the implementation of an irradiance (solar light intensity) sensor, and a full range of data for every day I wished to simulate.

Experimental Optimization

In lieu of simulation, I have opted for an experimental approach to system optimization. I will modify the PID control parameters, record data, and compare the gain of the system to other days in the same profiles. This approach will gradually yield the optimal control parameters. For this purpose, all that is required for comparison is the overall energy gain of the solar water system per day.

CHAPTER III

RESULTS

Control Board

The first, and primary result of my work is the controller circuit board. Pictures of the front and back of the partially assembled control board are included in Figures III.1 and III.2. The circuit board design and layout are included in **Appendices A and B**. This board achieved its purpose as a combination data logger and DC motor controller, with manual (LCD and pushbuttons) and USB communication interfaces. The board is able to record all system temperatures and flow readings at approximately a 1-second time period, record the data every 1 minute, and upload the data to the file server every 15 minutes, or as requested. An example of the recorded data is shown in Figure III.3. This data is saved in a date-stamped ".csv" file. Each row includes a time-stamp, 8 system temperatures in degrees Celsius, and the daily flow counter in tenths of a gallon. A full day of temperature readings is show in Figure III.4. The numbering of the sensors in this figure follows:

0. Bottom of Electric Tank.
1. Top of Electric Tank.
2. To house after tempering valve regulates water to 130^oF.
3. Top of Solar Tank.
4. Bottom of Solar Tank.
5. Solar Tank to collector.
6. Ambient temperature on the roof.

7. Returning from collector to Solar Tank.

The control board has been recording data nearly continuously since August 2012, with sporadic downtime for firmware upgrades. In addition, the board has been controlling the solar water heating system since January 2013, with sporadic downtime for control system optimization.

Verification

Analysis Results

The second result of my work is the verification that: (a) my controller board and proportional control scheme worked, and (b) that they worked better than the previous control system. By reproducing my control algorithm in MATLAB using the recorded temperature data, I constructed a view of the HTF pump duty ratio over the course of a day. This duty ratio is shown in Figure III.5, along with the temperature at the output of the solar collector, the temperature at the bottom of the solar storage tank, and the delta between these temperatures. This delta is the PID control scheme's "error" used to set the duty ratio. Figure III.6 shows the results of my data analysis. The first and second columns give the profile specifications of cloud coverage and average daily temperature from 10am to 6pm. When I ran my analysis, there were a total of 55 profiles. The only ones shown in Figure III.6 are the profiles containing matches between days running the old system, and days running the new system. The columns labeled "Num. Days" indicate how many days exist in each profile running each control method: either old or new. The columns labeled "Avg. Gain" indicate the average daily energy gain for each control method and each profile. The final column, labeled "Increase," indicates the percentage gain of the new system over the old system for each matched profile.

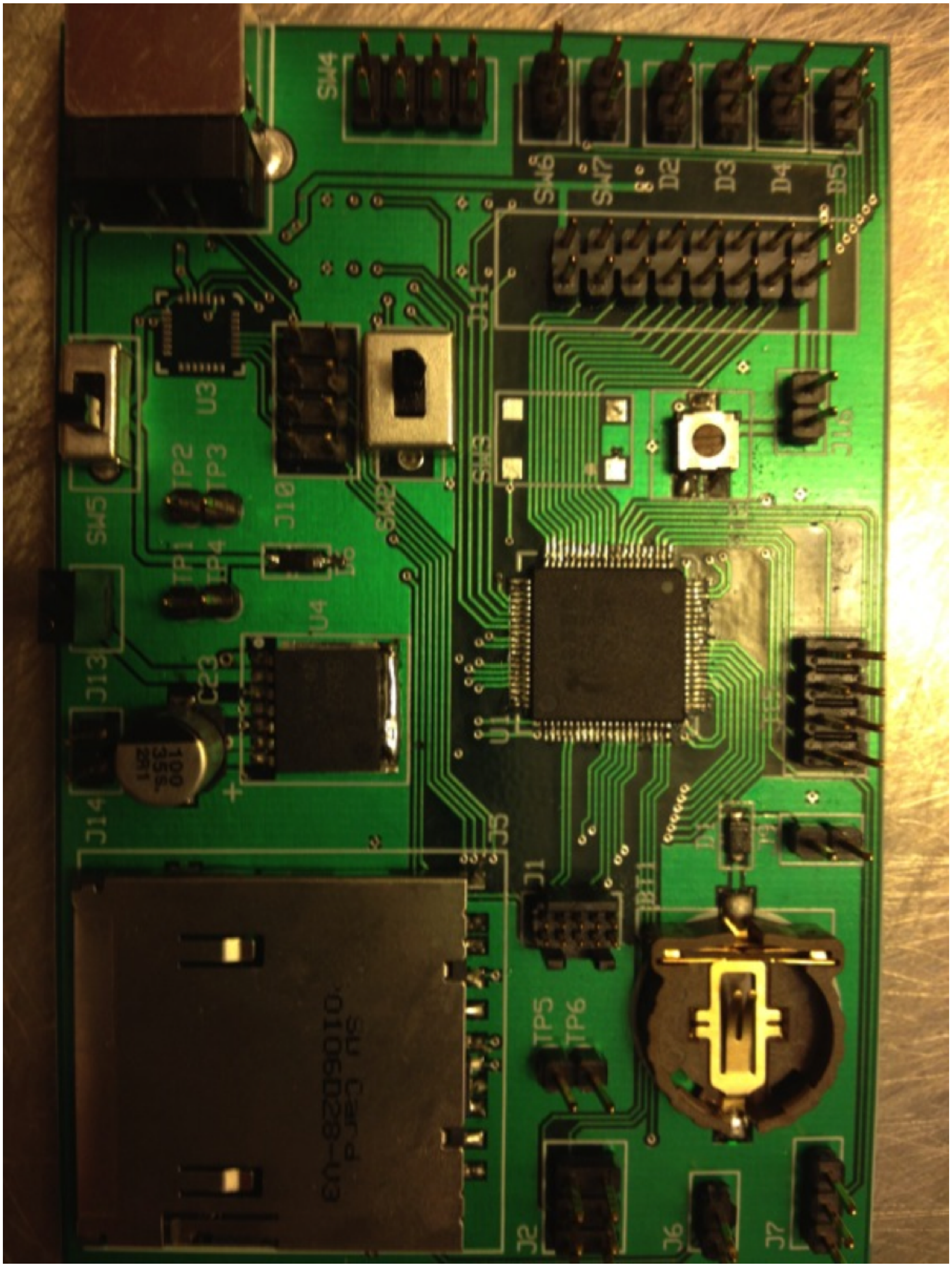

Fig. III.1. The assembled controller board. Actual size is 2.5 by 3.8 inches.

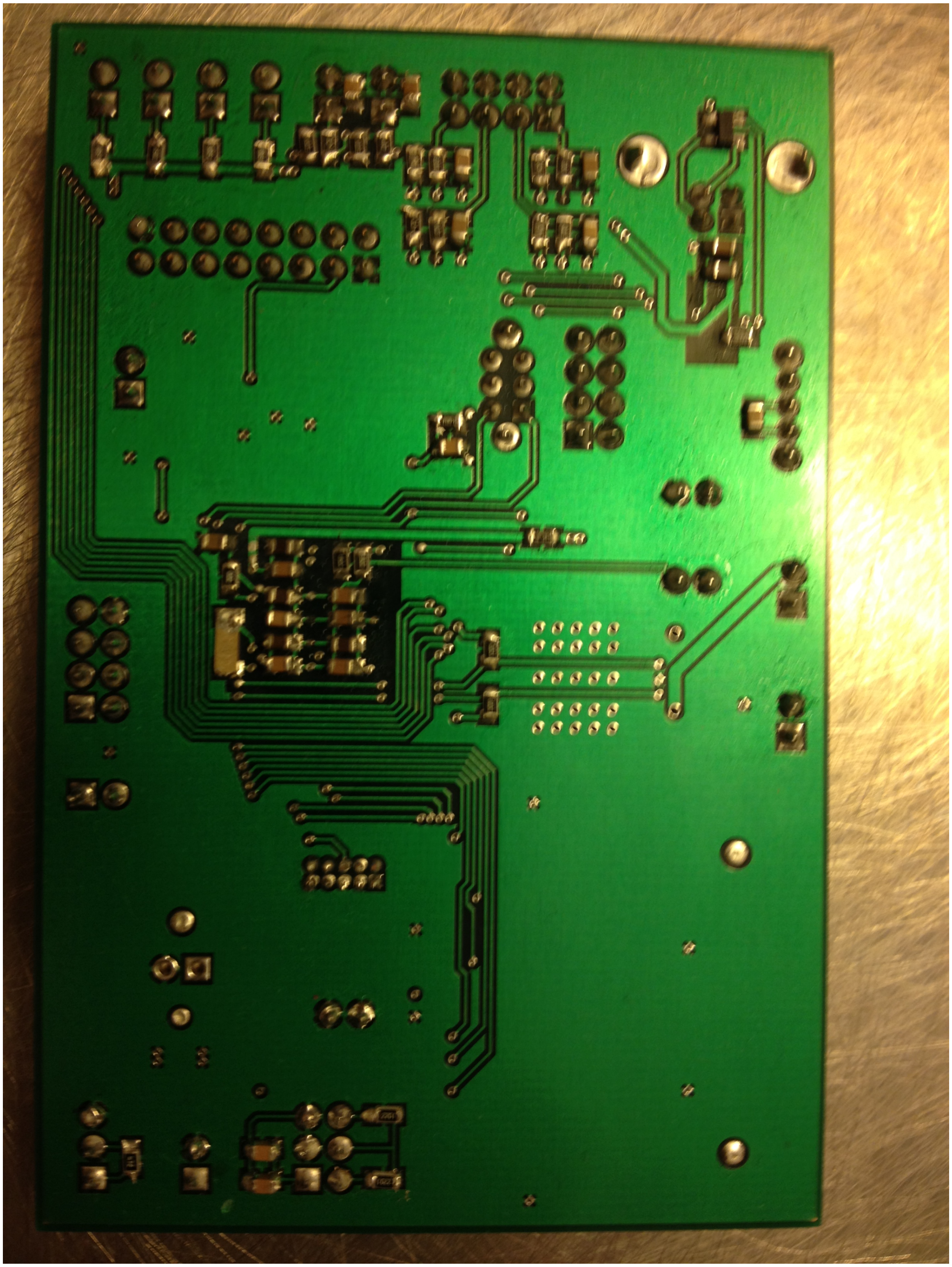

Fig. III.2. Back of the assembled controller board. Actual size is 2.5 by 3.8 inches. Most of the passive elements on the board are placed on the back.

```
10,35,00,42.8125,38.3125,33.3125,32.5625,25.2500,16.2500,18.5000,20.3750,114
10,36,00,42.8125,38.3125,33.0000,32.5625,25.1875,16.2500,18.5000,20.9375,115
10,37,00,42.8125,38.3125,32.7500,32.5625,25.1875,16.2500,18.5000,21.4375,115
10,38,00,42.8125,38.3125,32.4375,32.5625,25.2500,16.2500,18.5000,22.0000,115
10,39,00,42.8125,38.3125,33.5625,32.5625,25.2500,16.2500,18.5000,22.5625,119
10,40,00,42.6875,38.2500,40.3125,32.5625,25.1875,16.2500,18.0000,23.0625,137
10,41,01,42.3750,38.3125,42.6250,32.5625,25.1250,16.2500,17.2500,23.6250,155
10,42,00,41.6250,38.4375,43.6875,32.5000,24.9375,16.2500,16.8125,24.0625,170
10,43,00,40.8750,38.5625,44.2500,32.4375,24.7500,16.2500,16.5625,24.5625,181
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10,45,00,40.1875,38.8125,44.6875,32.3750,24.1250,16.2500,16.5000,25.6875,206
```

Fig. III.3. SHWP_DATA_02_02_2013.csv: Example of data recorded by circuit board and saved on data server. Total file is 1440 rows long, the number of minutes in a day.

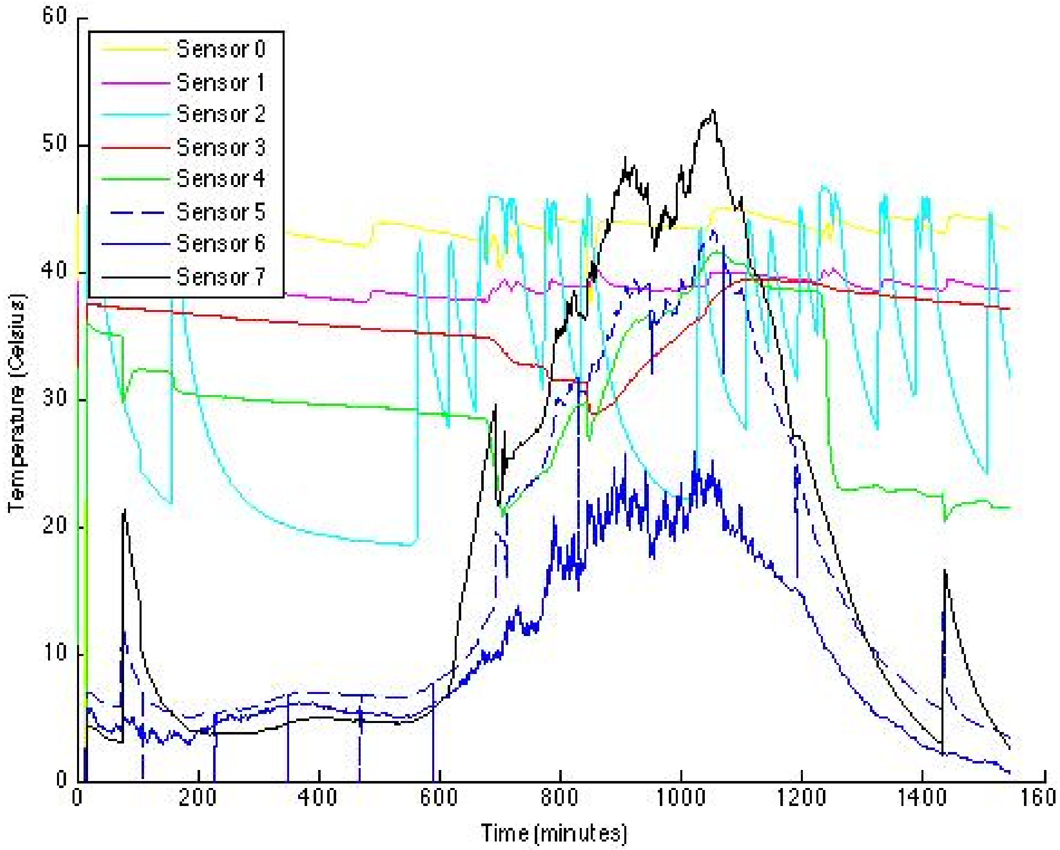


Fig. III.4. Recorded temperature data for Feb. 28, 2013.

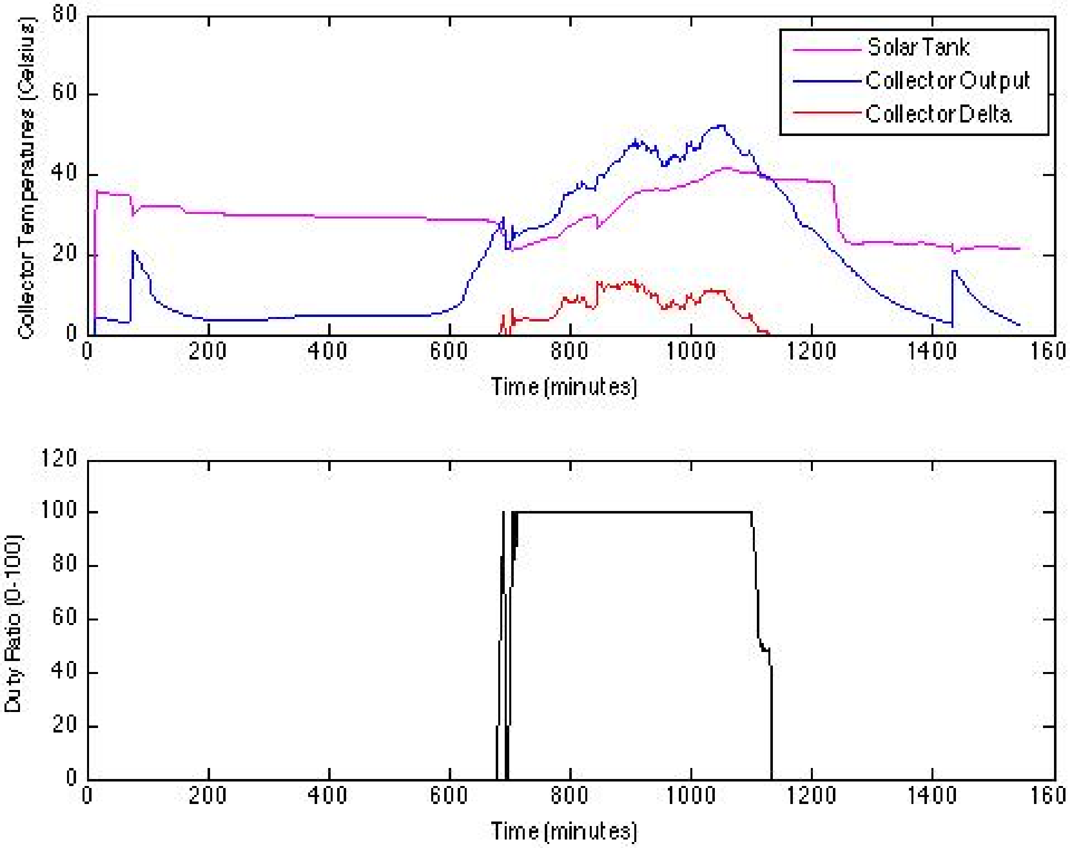


Fig. III.5. Recorded temperature and flow rate data for Feb. 28, 2013.

Profile		Old System		New System		
Cloud Coverage	Av. Temp.	# Days	Av. Gain	# Days	Av. Gain	Increase
Clear	37.6-43.2	1	1.98	3	6.31	218.28%
Clear	43.2-48.8	1	2.99	2	2.89	-3.46%
Clear	54.4-60	2	3.99	6	5.52	38.33%
Clear	60-65.6	2	1.26	6	5.30	319.27%
Clear	71.2-76.8	5	2.56	2	7.84	206.16%
Clear	76.8-82.4	4	2.54	2	4.70	85.05%
Broken	71.2-76.8	1	0.97	1	7.59	678.53%
Broken	82.4-88	1	2.58	1	8.42	226.12%
Overcast	32-37.6	1	0.22	1	0.90	312.89%
Overcast	48.8-54.4	1	2.87	1	0.72	-74.81%
Overcast	71.2-76.8	1	1.22	1	6.98	471.85%
Overcast	82.4-88	1	0.94	1	5.68	504.71%

Fig. III.6. Table of average energy gains in profiles containing at least one match between control methods.

Comparison of Control Methods

A weighted average of the results in Figure III.6 shows that the newer PID control system gained an average 3.22 KWH more energy per day than the old hysteresis controller. This is a 206.57% increase in energy efficiency.

CHAPTER IV
DISCUSSION

Control Board

The solar water heating system controller board fulfilled all of its primary requirements. It is capable of interfacing with an arbitrary number of temperature sensors, counting the HTF flow rate, recording data, keeping time, and interfacing with the data server. However, I also designed the board with several secondary capabilities in mind that have not yet been implemented. With an extension of the microcontroller firmware, the board's automatic battery backup, on-board data storage on the SD memory card, and USB interface to replace the current UART communication method may be enabled. However, none of these functions are vital to the operation of the board, they simply improve the robustness of the system. The primary reason I would invest the time on these secondary capabilities is if I intended to take the system to the commercial market.

A more useful improvement is the addition of a spectrometer or more basic light sensor for the system. Such a sensor would allow me to determine and record the incident solar power in the form of radiation at any given time. With sufficient radiation data, any variety of control schemes and parameter values may be simulated to determine the most effective values for any type of day. This will allow me to fully optimize my system controller without having to resort to trial and error for each parameter value. Currently, there is not enough data to perform such a simulation, though all of the simulation code has been written.

Control Scheme

The primary goal of my research was to design an optimized control scheme for the solar water heating system. I accomplished this goal with a discretized PID controller implemented in the system control board's microcontroller. Using the data I have collected so far, this control scheme has been verified as more effective than the hysteresis controller my project replaced.

The primary reason for this improvement lies in the method of operation for a hysteresis, or "bang-bang" controller. A hysteresis controller has only 2 control settings: on and off. The hysteresis controller formerly used in the solar water heater observed the temperature difference between the solar collector and the solar tank. When this difference was greater than 8 degrees Fahrenheit, the system turned on. When this difference was less than 8 degrees Fahrenheit, the system turned off. This simple control method led to some very ineffective behavior.

First, on colder days when the observed temperature differential never reached 8^oF, the system would never turn on. In contrast, the PID controller is capable of sustaining a minuscule temperature delta; allowing it to gather energy on very cold days.

Second, when the heat transfer fluid in the collector heats up and the hysteresis controller first turns on, all of the heated water is quickly cycled out of the collector, and is replaced with colder water previously in the unheated pipes. The solar collector cannot heat the water quicker than the system can cycle. When the temperature sensor in the collector senses the colder fluid, the system shuts off, and the cycle repeats. This behavior causes an erratic oscillation in the system, stressing the HTF pump, and shortening the lifetime of the system. In contrast, the proportional nature of the PID controller allows the HTF flow rate to build up gradually, tracking the energy input from the solar collector, and preventing oscillations.

For a more robust comparison, I will need to wait until the summer so I can compare the two control methods across all types of days; as defined by average daytime temperature and categorical cloud coverage. Based on my preliminary results, I fully expect this comparison to favor the PID controller. However, I expect the average increase in energy gain across all types of days to be more moderate than the gains seen in my preliminary data. This is because all of my preliminary data was taken this winter, and the new control scheme is most effective during days with lower available energy. On a sunny summer day, any reasonable control system will simply run the HTF as fast as possible for most of the day.

Energy Gain Comparison

Using the results in Figure III.6, I computed an average energy gain for each control method, weighted by the number of days in each profile. The final result is that for the considered days, the newer PID control system gained 3.22 KWH more energy than the old hysteresis controller. This is an average 206.57% increase in energy efficiency.

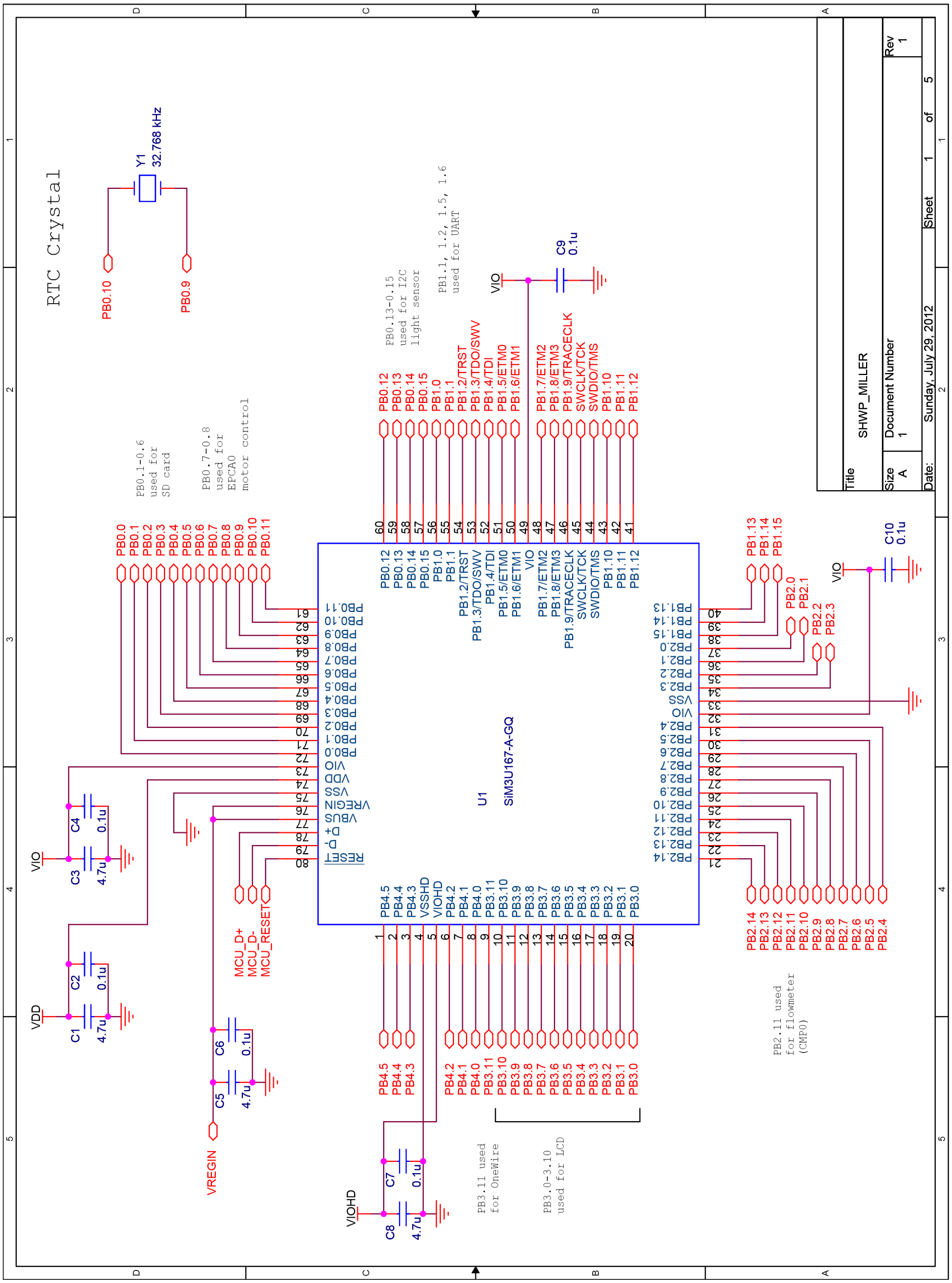
Although this number may seem abnormally high, it is actually a reasonable result. All of the data recorded by the system has occurred in the late fall and in the winter. The old controller required an 8^oF temperature difference between the solar collector and tank to even turn on. Therefore, on relatively cold days, the system would either turn on for a very short period of time in the middle of the afternoon, or not turn on at all. In contrast, due to its proportional nature, the PID controller runs at a minimum temperature difference of 1^oC. This makes the PID controller effective even on cold days. I expect the difference between the gains of the systems to be less noticeable on warmer days during the summer, when the system quickly reaches its maximum transfer rate and holds it for most of the day.

Further Improvements of Energy Gain

There are many additional improvements that may be made to optimize this solar water heating system. A comprehensive plan for my future work on this project is included in **Appendix C - Future Work**.

APPENDIX A

CONTROL BOARD SCHEMATIC


RTC Crystal
Y1
32.768 kHz
PB0.10
PB0.9
PB0.1-0.6 used for SD card
PB0.7-0.8 used for EPCA0 motor control
PB0.13-0.15 used for I2C light sensor
PB1.1, 1.2, 1.5, 1.6 used for UART
VIO
C9
0.1u
VDD
C1
4.7u
C2
0.1u
C3
4.7u
C4
0.1u
C5
4.7u
C6
0.1u
C7
0.1u
C8
4.7u
C10
0.1u
VREGIN
VIOHD
MCU_D+
MCU_D-
MCU_RESET
U1
SiM3U167-A-GQ
PB0.0
PB0.1
PB0.2
PB0.3
PB0.4
PB0.5
PB0.6
PB0.7
PB0.8
PB0.9
PB0.10
PB0.11
PB0.12
PB0.13
PB0.14
PB0.15
PB1.0
PB1.1
PB1.2/TRST
PB1.3/TDO/SWV
PB1.4/TDI
PB1.5/ETM0
PB1.6/ETM1
PB1.7/ETM2
PB1.8/ETM3
PB1.9/TRACECLK
SWCLK/TCK
SWDIO/TMS
PB1.10
PB1.11
PB1.12
PB1.13
PB1.14
PB1.15
PB2.0
PB2.1
PB2.2
PB2.3
PB2.4
PB2.5
PB2.6
PB2.7
PB2.8
PB2.9
PB2.10
PB2.11
PB2.12
PB2.13
PB2.14
PB3.0
PB3.1
PB3.2
PB3.3
PB3.4
PB3.5
PB3.6
PB3.7
PB3.8
PB3.9
PB3.10
PB3.11
PB4.0
PB4.1
PB4.2
PB4.3
PB4.4
PB4.5
VSSHD
VIOHD
VIO
VDD
VSS
VREGIN
VBUS
D+
D-
RESET
PB2.11 used for flowmeter (CMP0)
PB3.11 used for OneWire
PB3.0-3.10 used for LCD
Title
SHWP_MILLER
Size
A
Document Number
1
Rev
1
Date: Sunday, July 29, 2012
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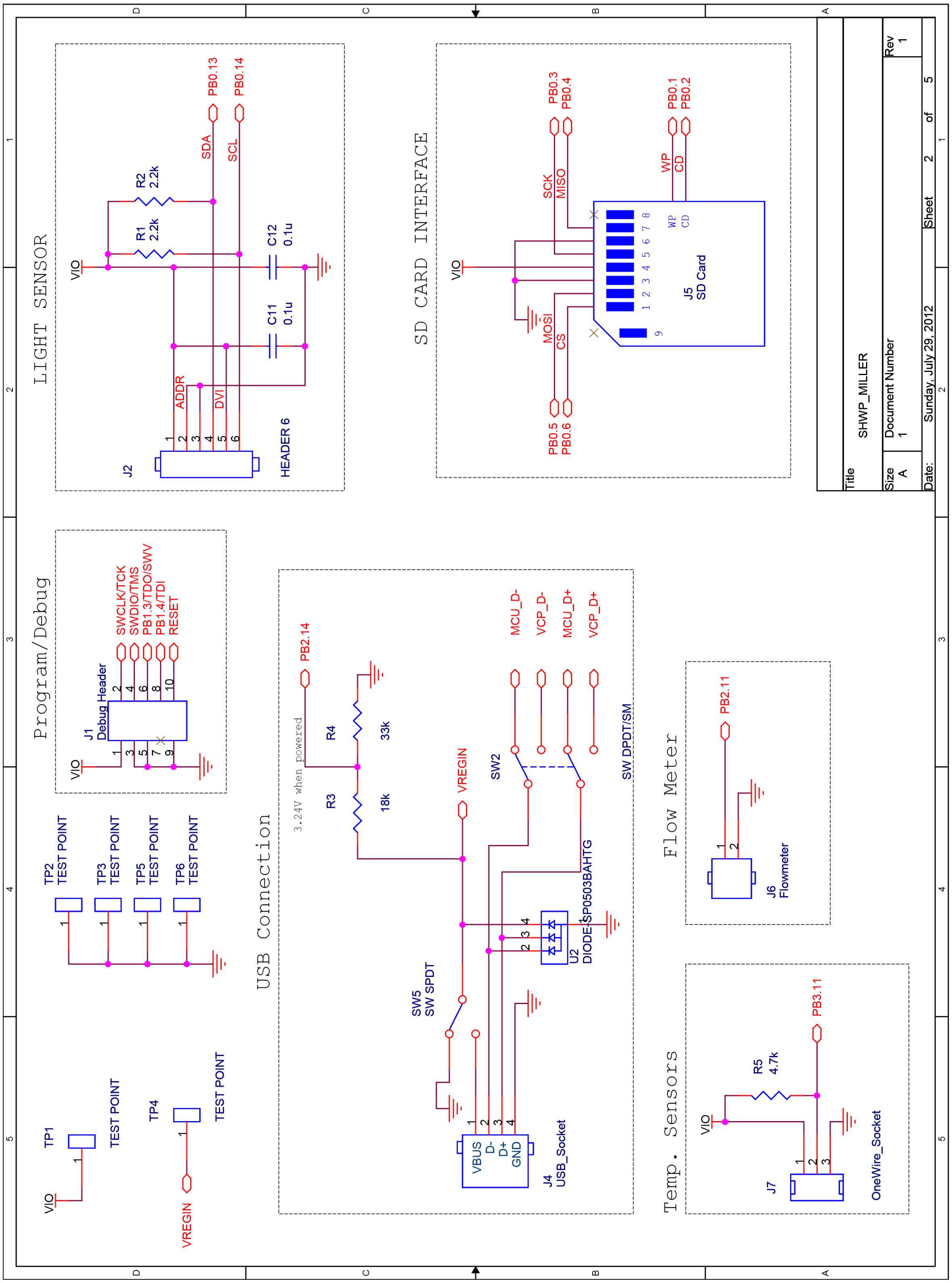

LIGHT SENSOR
VIO
R1
2.2k
R2
2.2k
SDA
SCL
PB0.13
PB0.14
C11
0.1u
C12
0.1u
ADDR
DVI
J2
HEADER 6
SD CARD INTERFACE
SCK
MISO
MOSI
CS
PB0.3
PB0.4
PB0.5
PB0.6
WP
CD
PB0.1
PB0.2
J5
SD Card
Program/Debug
J1
Debug Header
SWCLK/TCK
SWDIO/TMS
PB1.3/TDO/SWV
PB1.4/TDI
RESET
TP1
TEST POINT
TP2
TEST POINT
TP3
TEST POINT
TP4
TEST POINT
TP5
TEST POINT
TP6
TEST POINT
VREGIN
USB Connection
3.24V when powered
PB2.14
R3
18k
R4
33k
SW2
SW DPDT/SM
MCU_D-
VCP_D-
MCU_D+
VCP_D+
SW5
SW SPDT
U2
DIODE-SP0503BAHTG
J4
USB_Socket
VBUS
D-
D+
GND
Flow Meter
PB2.11
J6
Flowmeter
Temp. Sensors
R5
4.7k
PB3.11
J7
OneWire_Socket
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Size
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1
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Sunday, July 29, 2012
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2
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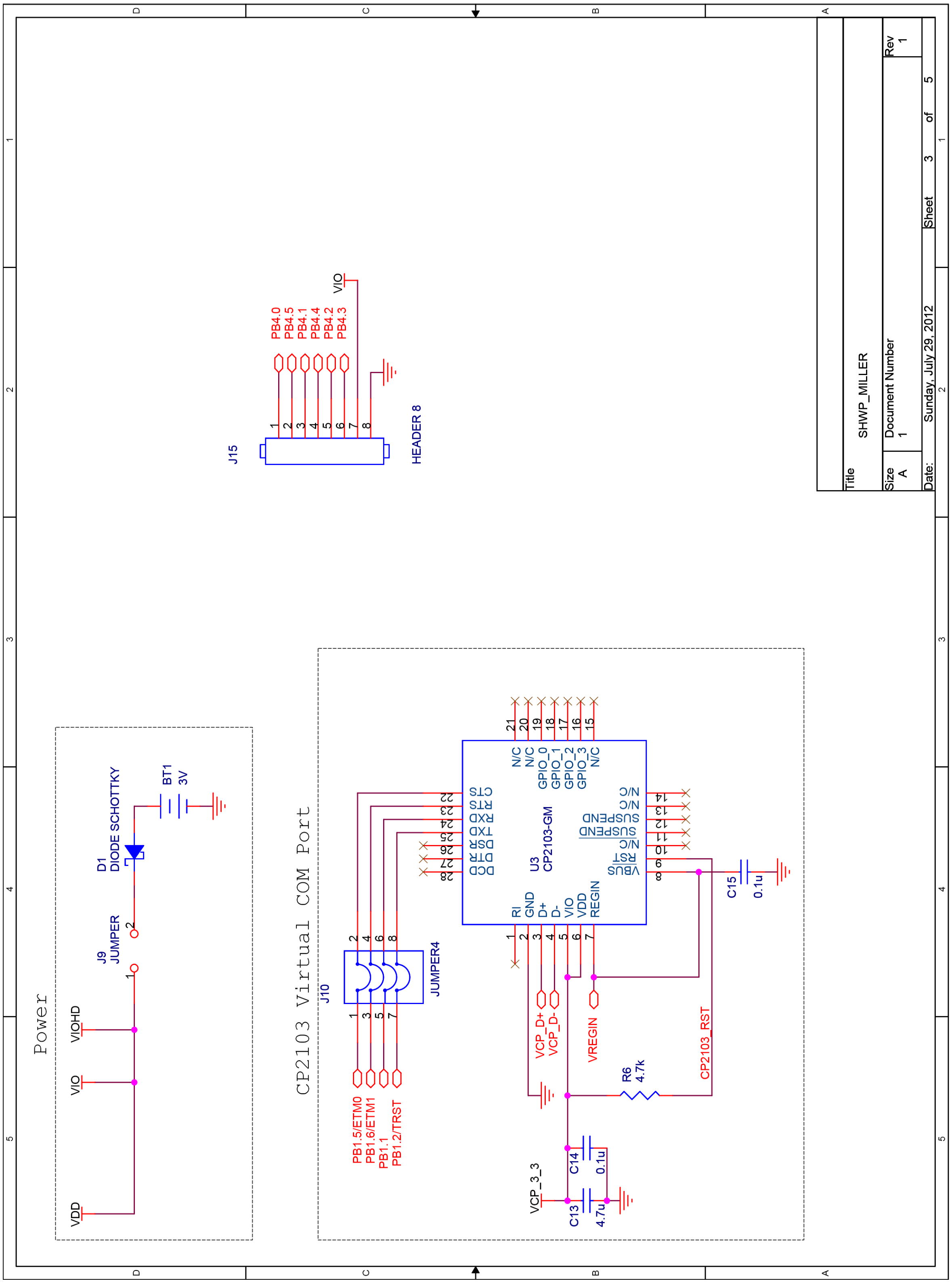
5



Power
VDD
VIO
VIOHD
J9
JUMPER
D1
DIODE SCHOTTKY
BT1
3V
CP2103 Virtual COM Port
J10
JUMPER4
PB1.5/ETM0
PB1.6/ETM1
PB1.1
PB1.2/TRST
U3
CP2103-GM
RI
GND
D+
D-
VIO
VDD
REGIN
DCD
DTR
DSR
TXD
RXD
RTS
CTS
N/C
GPIO_0
GPIO_1
GPIO_2
GPIO_3
SUSPEND
VBUS
RST
VCP_D+
VCP_D-
VREGIN
CP2103_RST
R6
4.7k
C13
4.7u
C14
0.1u
C15
0.1u
VCP_3_3
J15
HEADER 8
PB4.0
PB4.5
PB4.1
PB4.4
PB4.2
PB4.3
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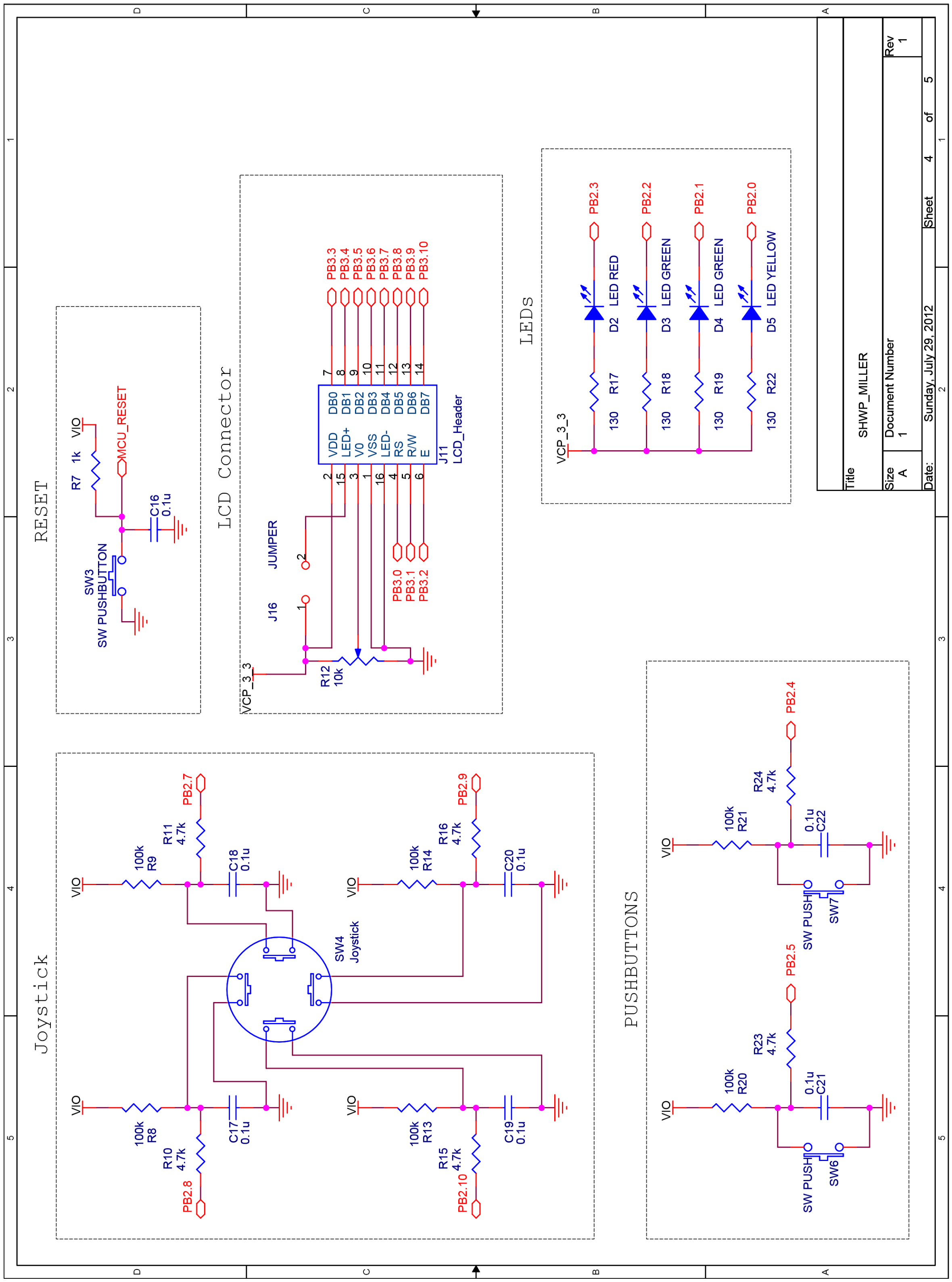
RESET
SW3
SW PUSHBUTTON
R7 1k
VIO
MCU_RESET
C16
0.1u
LCD Connector
J16
JUMPER
VCP_3_3
R12
10k
PB3.0
PB3.1
PB3.2
VDD
LED+
V0
VSS
LED-
RS
R/W
E
DB0
DB1
DB2
DB3
DB4
DB5
DB6
DB7
J11
LCD_Header
PB3.3
PB3.4
PB3.5
PB3.6
PB3.7
PB3.8
PB3.9
PB3.10
LEDs
R17
R18
R19
R22
130
D2 LED RED
D3 LED GREEN
D4 LED GREEN
D5 LED YELLOW
PB2.3
PB2.2
PB2.1
PB2.0
Joystick
100k R8
100k R9
R10 4.7k
R11 4.7k
C17 0.1u
C18 0.1u
PB2.8
PB2.7
SW4
Joystick
100k R13
100k R14
R15 4.7k
R16 4.7k
C19 0.1u
C20 0.1u
PB2.10
PB2.9
PUSHBUTTONS
100k R20
100k R21
R23 4.7k
R24 4.7k
0.1u C21
0.1u C22
PB2.5
PB2.4
SW PUSH
SW6
SW7
Title
SHWP_MILLER
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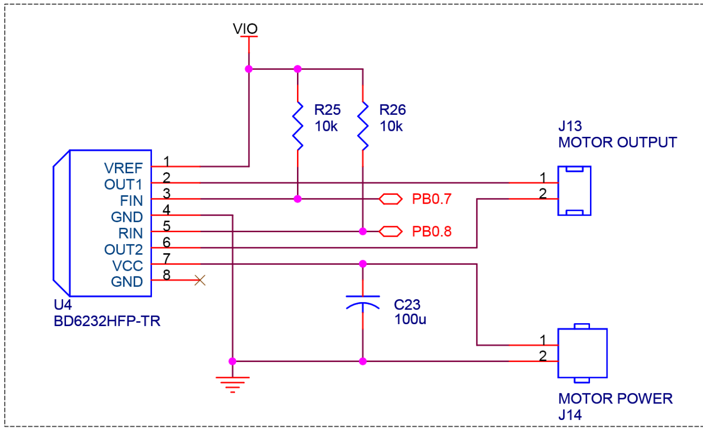
H-Bridge Motor Driver

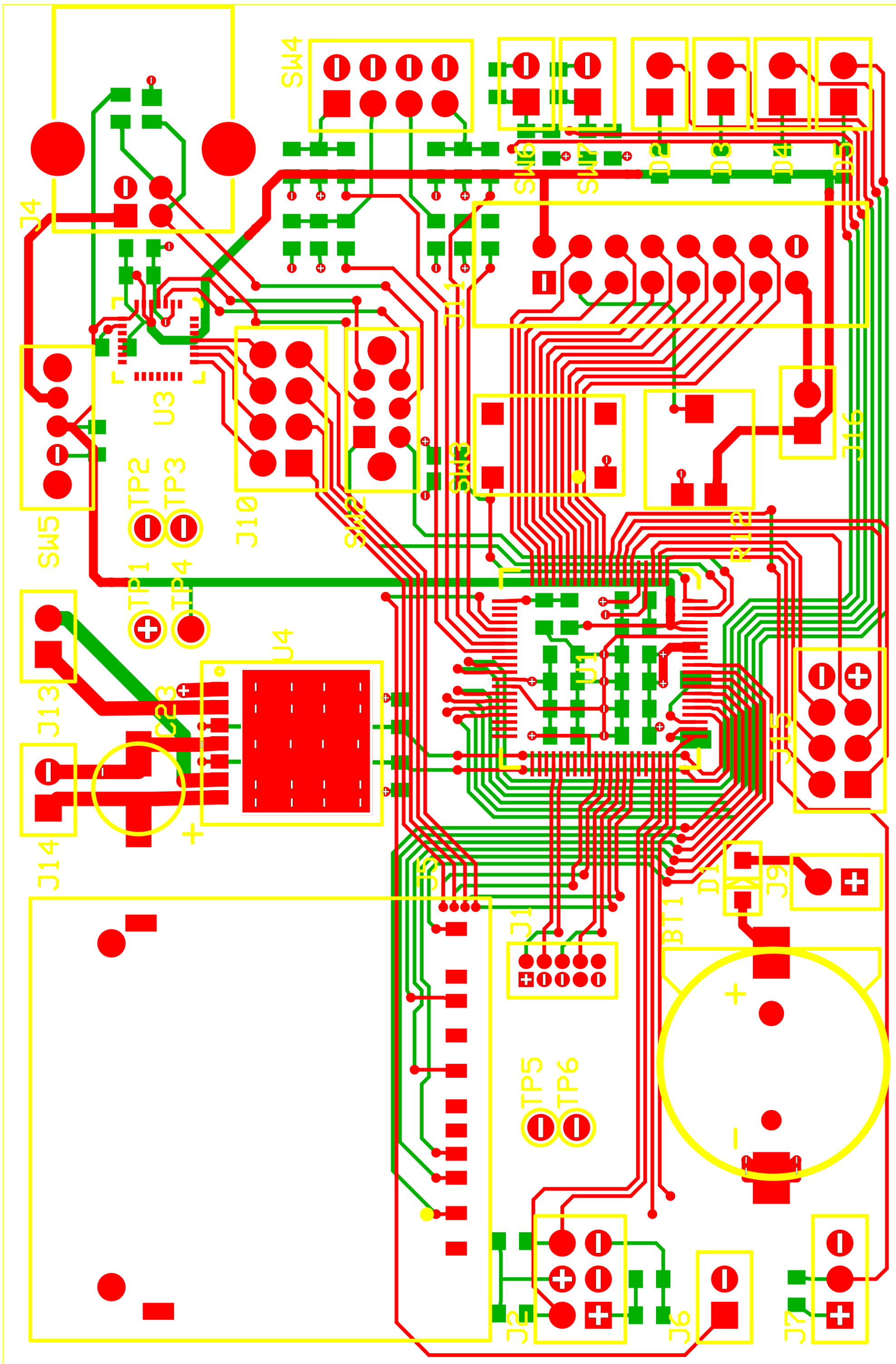


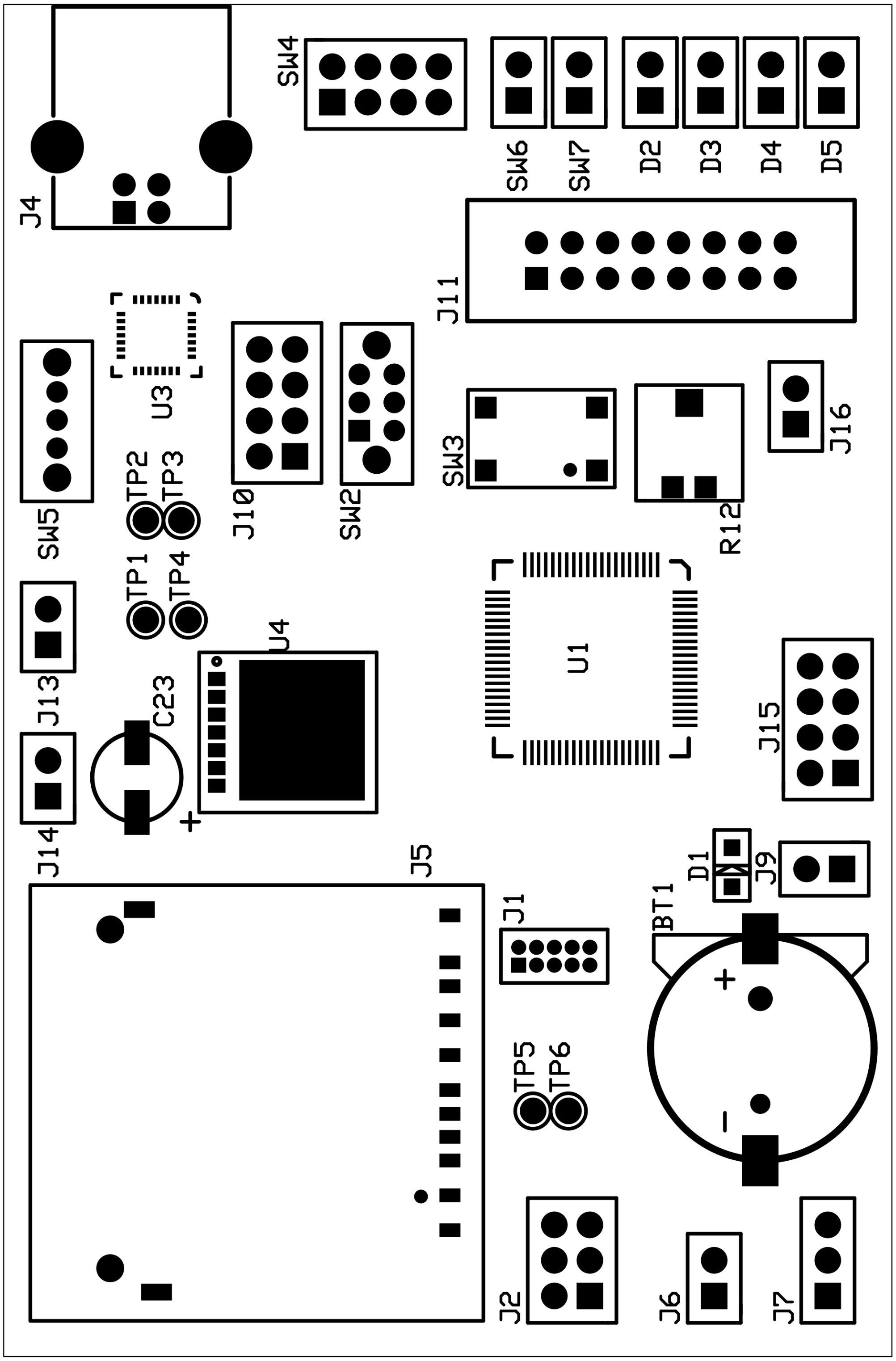
	FIN	RIN	VREF	OUT1	OUT2	Operation
a	L	L	X	Hi-Z*	Hi-Z*	Stand-by (idling)
b	H	L	VCC	H	L	Forward (OUT1 > OUT2)
c	L	H	VCC	L	H	Reverse (OUT1 < OUT2)
d	H	H	X	L	L	Brake (stop)
e	PWM	L	VCC	H	$\overline{\text{PWM}}$	Forward (PWM control mode A)
f	L	PWM	VCC	$\overline{\text{PWM}}$	H	Reverse (PWM control mode A)
g	H	PWM	VCC	$\overline{\text{PWM}}$	L	Forward (PWM control mode B)
h	PWM	H	VCC	L	$\overline{\text{PWM}}$	Reverse (PWM control mode B)
i	H	L	Option	H	$\overline{\text{PWM}}$	Forward (VREF control)
j	L	H	Option	$\overline{\text{PWM}}$	H	Reverse (VREF control)

Title: SHWP_MILLER		
Size: A	Document Number: 1	Rev: 1
Date: Tuesday, July 24, 2012	Sheet 5 of 5	

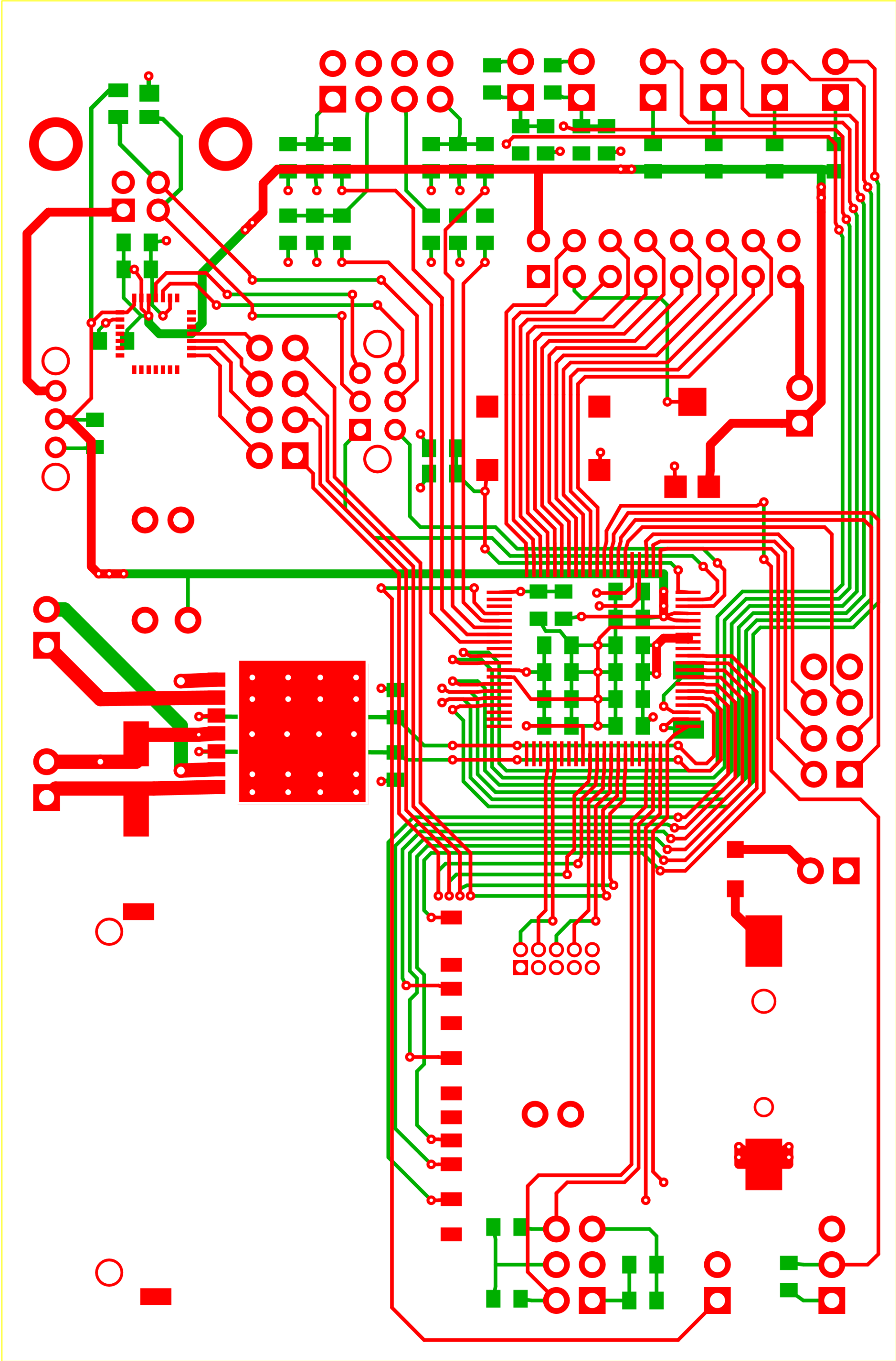
APPENDIX B

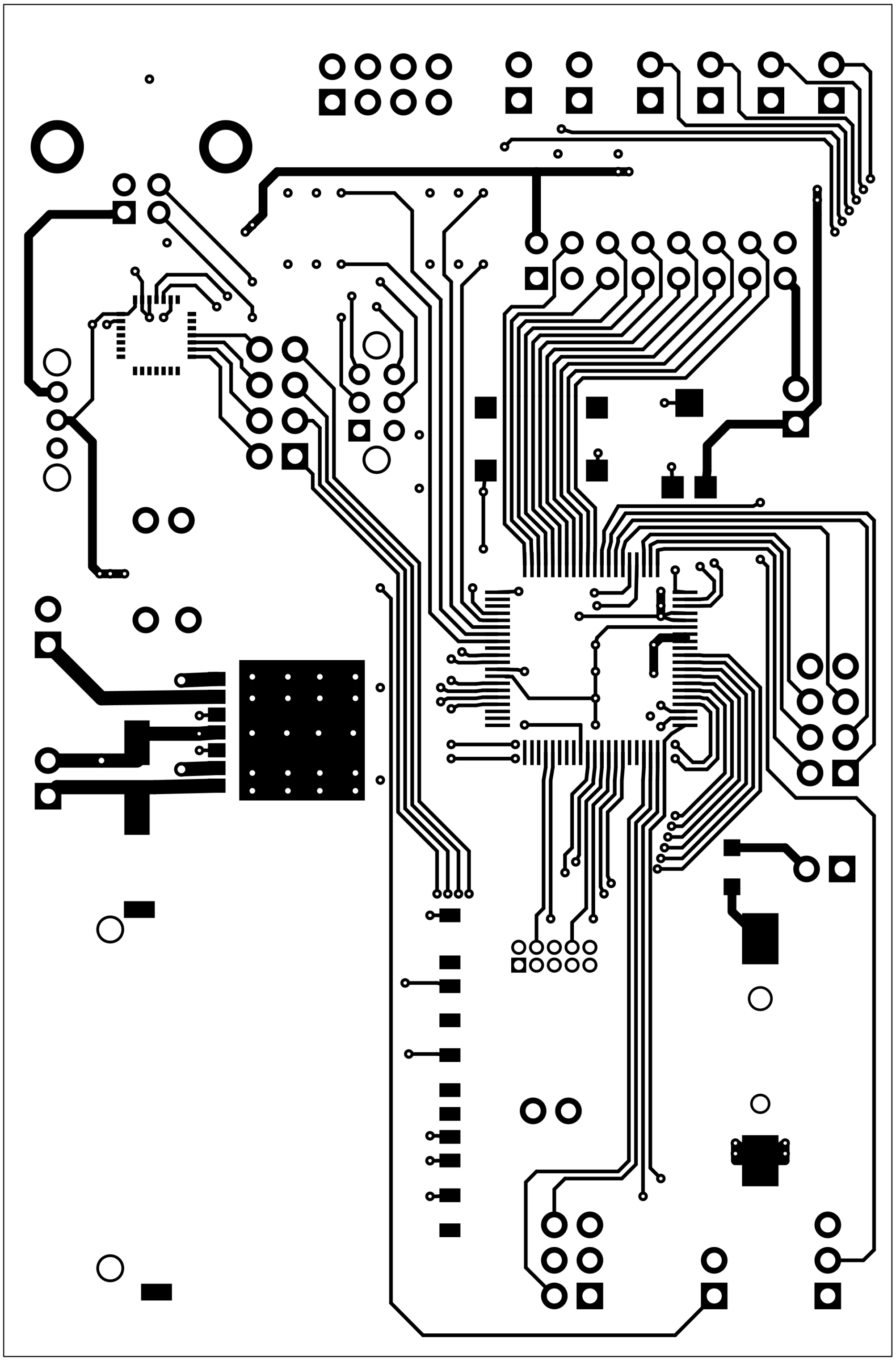
CONTROL BOARD LAYOUT

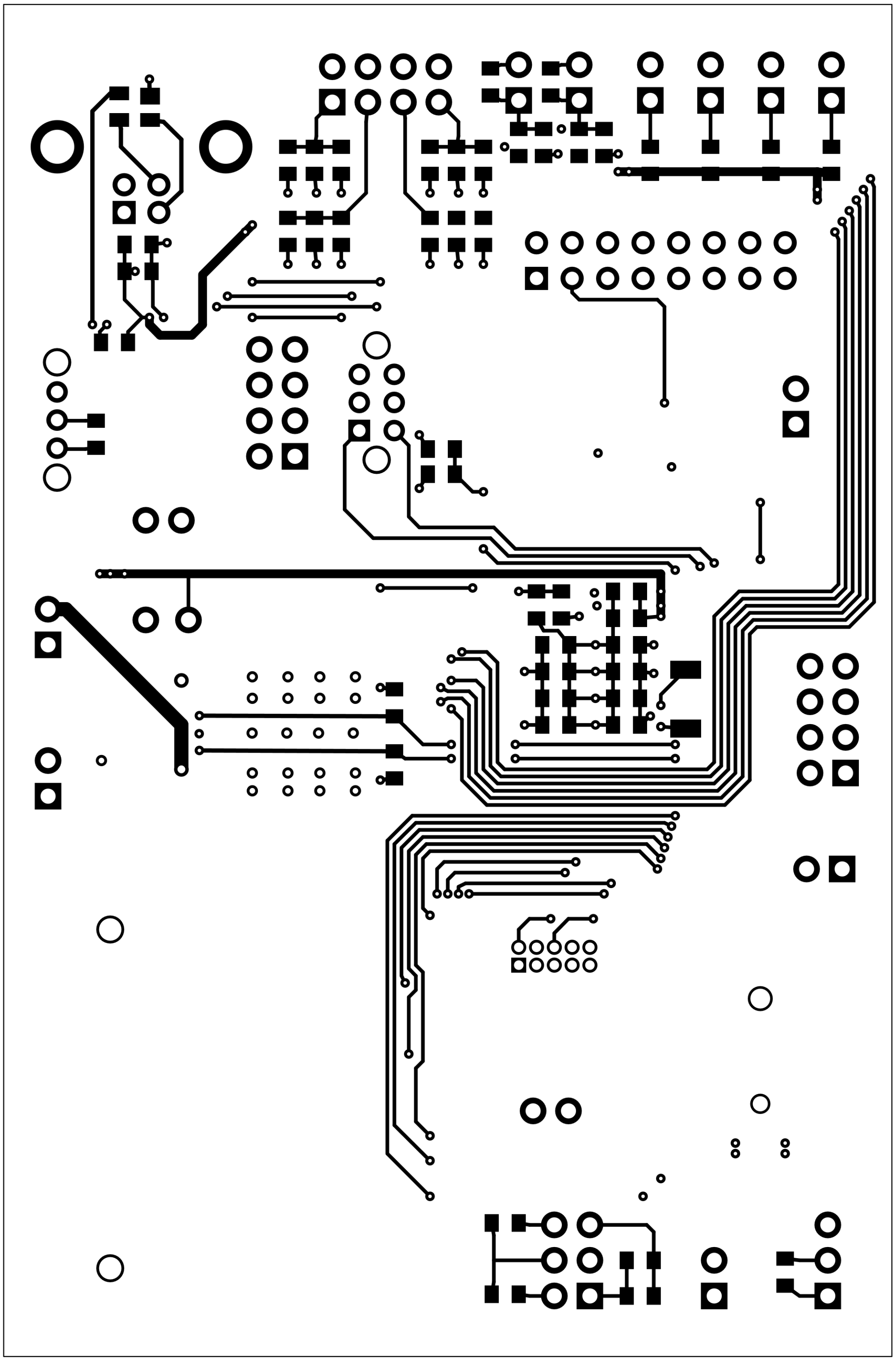

J4
SW4
SW6
SW7
D2
D3
D4
D5
J11
U3
J10
SW2
SW3
R12
J16
SW5
TP1
TP2
TP3
TP4
J13
C23
U4
J14
U1
J15
J5
J1
D1
J9
BT1
TP5
TP6
J2
J6
J7



J4
SW4
SW6
SW7
D2
D3
D4
D5
J11
U3
SW5
TP2
TP3
J10
SW2
SW3
R12
J16
TP1
TP4
U4
U1
J13
C23
J15
J14
J5
D1
J9
J1
BT1
TP5
TP6
J2
J6
J7







APPENDIX C
FUTURE WORK

Thermoelectric Conversion of Excess Energy

In the future, the functionality of the solar water heating system may be extended by installing a thermoelectric generator. The purpose of this addition is twofold. Currently, the system has no way to deal with an excess in available energy. If the system overheats, the only option is to shut down until the system has cooled off due to passive heat loss to the environment. The addition of a thermoelectric generator would allow excess energy to be converted to electricity. In this way, the system could continue to be of financial benefit. Additionally, the conversion of stored thermal energy to electricity opens up new avenues for optimizing the system's efficiency.

Predictive Control

One such avenue is for the system to dynamically adjust a prediction of the water usage of the home in which the system is installed. The system will also utilize weather predictions to anticipate the energy that will be available. These predictions will allow the system to convert all excess energy into electricity, thus minimizing the energy lost to thermal decay.

The four specific aims of this research are given below.

1. Implement the highest efficiency Seebeck thermoelectric generator possible, taking into account the cost/benefit ratio of the generator.
2. Develop an adaptive prediction of hot water usage based on historical data. This prediction will take into account patterns and habits of water usage.

3. Create a method by which the control system will gather weather predictions from the Internet. These predictions will not exceed two days in the future, to avoid extreme inaccuracies caused by the chaotic behavior of the weather.

4. Using the above predictions, develop a solar water heater control scheme that:

    a. Always meets the hot water needs of the house.

    b. Maximizes the amount of thermal energy converted to electricity.

Research Plan

The first part of the proposed research is to implement the thermoelectric generator. Prior to selecting a generator, the range of temperature differential ranges that the generator will experience, and the maximum power generation it will be required to handle must be determined. I will then perform a cost-benefit analysis of preexisting generators, versus a custom-built solution. This analysis will take into account cost, reliability, efficiency, and maximum power generation. At this point I will also decide on a heat-sink solution for the generator. The heat sink will likely be a ground-cooled passive pipe array.

The next stage of research will refer to the recorded data gathered by the existing system. This data will be used to develop an adaptive prediction of the hot water required by the household. This prediction will take into account habits and patterns of water usage. These patterns will be modeled by statistical methods, weighted by the age of the data. This will allow the system to take old patterns into account, but still autonomously adapt to changes in water usage habits.

Next, the control system will gather weather forecasts from the Internet. This will most likely be an action initiated by the Windows data server. To increase reliability, forecasts from multiple sources will be taken and weighted according to their respective reliabilities. The information gathered by the data server will be communicated to the control system via the already existing serial communication interface.

The final step of my research will be to develop a predictive control scheme to use the usage predictions and weather forecasts. This scheme will run in parallel to the already existing basic PID control scheme. This new control system will focus on maximizing the temperature differential between the solar collector and the storage tank by siphoning energy from the storage tank and converting it to electricity. Although this is a relatively inefficient process, depending on the specifications of the Seebeck generator, the electrical energy will not suffer heat losses, as it would in the thermal storage tank.

The difficulty in this step will be optimizing the system so that the household never notices the system is there. This will require a safety margin of thermal energy remaining in the storage tank. To optimize the system, this safety margin will vary based on the consistency of water usage in the house. If the house uses energy in a very consistent manner, the safety margin will be reduced. If the water usage is erratic, the safety margin will automatically increase, reducing overall efficiency, but ensuring the demands of the house are always met.