Solar Decathlon
Instrumentation and Controls
Final Project Report

by

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San Luis Obispo

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Statement of Disclaimer

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Executive Summary

The Instrumentation and Controls team has designed a control and instrumentation system for the 2015 Cal Poly Solar Decathlon house that will monitor temperature, humidity, and energy usage throughout the house and control the phase change material duct. It will relay information to the user through a tablet application developed by the Computer Science team. The team has also designed a lighting control scheme for use with Lutron's HomeWorks QS lighting control system.

Chapter 1 Introduction

The Instrumentation and Controls Engineering (ICE) team has designed and will be implementing the home automation system for the Cal Poly Solar Decathlon 2015 house including the sensors and controllers.

Solar Decathlon 2015

The Solar Decathlon is a biennial competition hosted by the US Department of Energy that has college teams compete to build an innovative solar-powered house. There are 10 contests, each worth 100 points, for a total of 1000 points: Architecture, Market Appeal, Engineering, Communications, Affordability, Comfort Zone, Appliances, Home Life, Commuting, and Energy Balance. The winner of the Decathlon is the team with the highest total number of points. The 2015 Solar Decathlon will he held in Irvine, CA in October.

Problem Definition

The Cal Poly Solar Decathlon team needs a dedicated team to design a control system for their house. The control system needs to intelligently automate the lights throughout the house and monitor conditions in the house such as temperature and energy usage.

Objectives

The overall goal of our team is to control the solar house’s indoor lighting, monitor energy usage, and pass information to and from the app developed by the Computer Science (CS) team.

The below engineering specifications are subject to change, removal, and addition. The Quality Function Deployment method led us to create the specs specifically to fulfill the customer requirements that the control system be: cheap, energy efficient, sustainable, comfortable, modern, visually appealing, easy to use, and marketable. Appendix A shows the House of Quality created to map out all the specs, customer requirements, competing products, relative priority of each engineering spec and customer requirement, and the possible impacts each engineering spec will have on each other and how well they correlate to the customer requirements.
The values under the 5 different customer columns of the House of Quality show the relative importance (given as a percentage) that of each requirement for each customer. The values under the Current Product Assessment columns contain a rating out of 5 showing how well the competing products are fulfilling the customer requirements.

Table 1. Engineering Specifications For Lighting Systems

Design Parameter	Value	Tolerance	Compliance Method
Cost of Parts	$2000	±$1000	Analysis
Power Draw of Control Systems	400W	±200W	Test
Min Operating Temperature	-20˚F	±10˚F	Analysis, Inspection
Max Operating Temperature	200˚F	±20˚F	Analysis, Inspection
Expected Longevity	30 years	±7 years	Similarity to Existing Designs
Max Deviation from Set Constant Illuminance	50 lux	±10 lux	Test
Max Wall Footprint Area of Sensors	6 in^2	±2 in^2	Inspection
Max # of User Controls	8	±2	Inspection

Project Management Plan

The members of the ICE team each have positions with different responsibilities. Tim Ambrose is the Communications Officer, Mateo Begue is the Team Progress Officer, and Andrew Elliott is the Build Officer. Tim is the point of contact (POC) for our group.

Tim shall handle any communications with other subsystem teams including the EE team. Tim shall remain in contact with the rest of the subsystem teams to discuss potential systems that need to be controlled. He will also be in charge of emailing the sponsor and solar decathlon officers. Tim will also be the primary Revit user for the instrumentation and controls team.

As the team progress manager, Mateo shall create a management plan. This plan will include all of the major milestones needed for the solar decathlon and the senior project design course. One of Mateo's responsibilities is to document the progress of the project. This information will be logged into his notebook and it will be monitored by weekly status reports with Professor Schollenberger.

Andrew is the build officer. He is the mechanical engineering student and shall be in charge of manufacturing considerations and prototype fabrications if need be. Once the control systems are created, Andrew will have the task of testing the systems. Since Andrew is the only member with a yellow tag to operate machinery, he will be the member to operate machinery if needed.

See Appendix G for the team's Gantt chart.

Chapter 2 Background

There are quite a few interesting automation designs created by past Solar Decathlon teams, as well as existing technology and research that might be able to do what we need done.

Previous Decathlon Houses

The winning team in the 2013 Solar Decathlon, team Austria, created an automated screen and awning system that would move to shade the house during different times of the day. They also monitored their photovoltaic panels and energy usage, and controlled the house with a tablet application. The CS team is currently implementing a tablet application to control and monitor the house.

The University of Maryland won the 2011 Solar Decathlon. They automated the temperature, humidity, lighting, and more throughout their house using Arduino microcontrollers connected to relays. Their documentation is referenced in Appendix B. We plan to control our house similarly, with Arduino microcontrollers connected to sensors and relays.

Team Germany won the Solar Decathlon in 2009. They automated the slats covering their windows so that they could either block light or let light pass through. We considered implementing motorized shades to work in conjunction with our automatic light system to control heat and light from the environment.

Team Ontario got first place in the Engineering category in the 2013 Solar Decathlon. They predicted the weather using a connection to the internet and moved their shading and solar panels appropriately on a day by day basis. They also created a mobile phone application to control their house. They don't have any of these things on their construction drawings, but we don't think that implementing either of these ideas is very practical.

Existing Products

Upward Automation is a startup that has offered us the use of some of their code, but does not yet have existing products.

Marvell Smart LED lighting sells lighting drivers and control integrated circuits that work well for home automation systems.

Wink Hub sells a hub that connects with many different brands of smart appliances and controls them all from one location.

Crestron offers residential lighting control systems that can integrate light sensing, light control, and shade control.

Existing Research & Standards
Satyen Mukherjee et al. wrote an informative paper on *Closed Loop Integrated Lighting and Daylighting Control for Low Energy Buildings* (Appendix B). We are planning on implementing a similar closed-loop feedback control system for the lights in the house, and this paper has additional insight into integrating it with a shading system.

Title 24 (Appendix B) states that low-efficacy light bulbs must be controlled by motion detectors such that they turn off within 30 minutes of someone leaving the room. Our LED bulbs should be classified as high-efficacy, but even if they aren't, we are designing our system to turn off lights 15 minutes after someone leaves a room.

We were advised by lighting designers in an architectural meeting to select outdoor bulbs that comply with IP66 standards.

Chapter 3 Design Development

These are the control and instrumentation options that we considered.

Lighting Control: Controlling the lighting with a series of Arduino Minis, Renard controllers, and solid-state relays.

Energy Monitoring: Implementing an energy monitoring system that uses current sensors or current loops to monitor the solar house's energy usage.

Active Shading: Controlling the sunlight entering through windows with either motorized blinds or electrically-tinted windows.

Instant Hot Water: Controlling the operation of the tankless-instant water heaters based on temperature of water from the solar thermal system.

Solar Cooker Positioning: Moving the solar cooker array based on the position of the sun in order to maximize heat transfer to thermal storage units.

Grey/Black Water Valve: Switching the flow of grey water to either the grey tank or black tank depending on the grey water tank level and waste water source.

Concept Selection

We created a weighted decision matrix to determine which controls projects to focus on. The following is a copy of that matrix.

Table 2. Decision Matrix for ICE Project Focus

	Weight	Lighting Controls		Energy Monitoring		Active Shading		Instant Hot Water		Solar Cooker		Grey/Black Valve	
Affordability	0.1	4	0.4	6	0.6	4	0.4	5	0.5	6	0.6	8	0.8
Ease of Implementation	0.3	4	1.2	5	1.5	6	1.8	6	1.8	3	0.9	9	2.7
Appearance	0.1	10	1	8	0.8	7	0.7	1	0.1	4	0.4	1	0.1
Practicality	0.2	8	1.6	9	1.8	7	1.4	5	1	8	1.6	5	1
Ease of Use	0.1	8	0.8	10	1	9	0.9	9	0.9	5	0.5	8	0.8
Cool Factor	0.2	8	1.6	6	1.2	5	1	3	0.6	6	1.2	1	0.2
Totals	1	6.6		6.9		6.2		4.9		5.2		5.6	

From the matrix, we determined that we should focus on lighting controls and energy monitoring, with the possibility of working on active shading or the grey/black water valve. The following is our preliminary design and analysis for lighting control and energy monitoring.

Lighting Control

The control system hub will be connected to multiple Arduino microcontrollers, which will each have an array of sensors and lights connected to it either distributed throughout the room or packaged within the same enclosure as the Arduinos. The tablet application created by the CS team will be connected wirelessly to the hub. This configuration is displayed below in Figure 1.

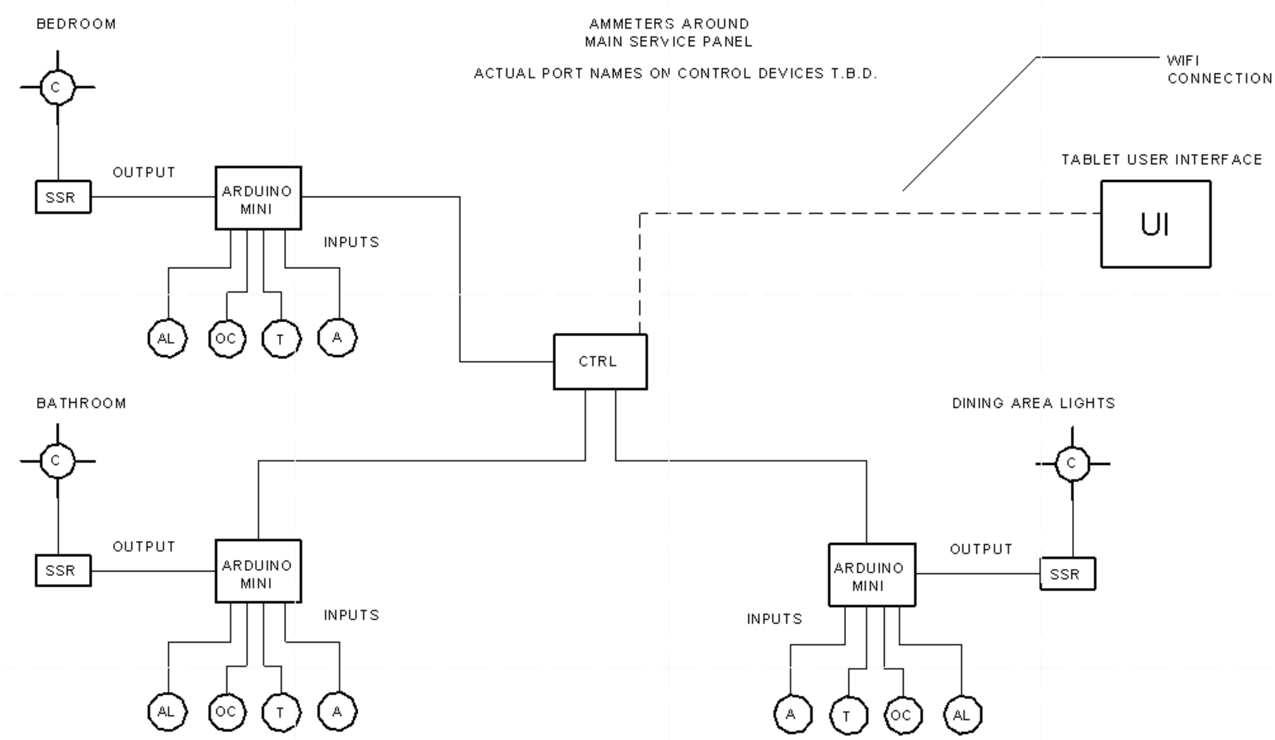


Figure 1. Functional Block Diagram of the Control System

RGB Lights

The idea of RGB lighting was thrown around for a while by members of the ICE and EE teams. The architects have shot down this idea, but are interested in creating an LED video wall on one side of the living room.

LED Lights

The architects are still designing the lighting in the house. It is certain that all or most of their fixtures will have LED bulbs.

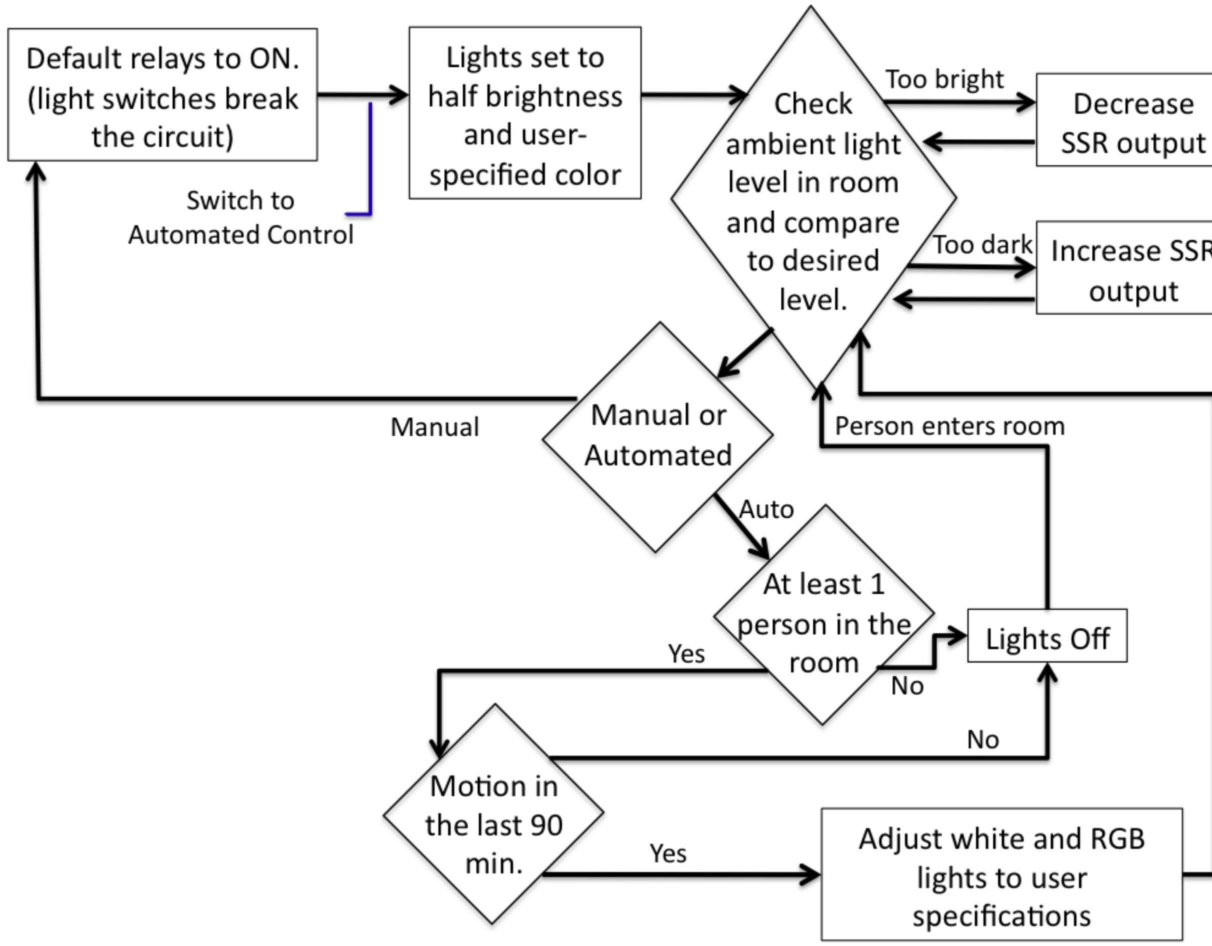


Figure 2. Lighting Control Algorithm

The lighting control algorithm will count the number of people in the room according to the order the motion sensors are tripped and switch off the lights after either 90 minutes of no motion or the count of people in the room goes to 0 and no motion is seen for 15 minutes. The ambient lighting will be kept at a constant level by measuring the ambient light in the room and adjusting the relay outputs when the sunlight contribution to ambient light decreases. This algorithm is shown graphically in Figure 2 above.

Energy Monitoring

The electrical engineering students will use current sensors clamped around the supply lines coming from the main service panel in order to measure energy use. They will gather this data using a data logger and send it to us. Additionally, a SmartMeter™ will measure the electricity generated by the solar panels so that the user can compare their power generation to their power consumption.

First Design

The following figure is the result of our first design, with all necessary components and their connections detailed. The Arduino Mini Detail Wiring shows the sensor connections to the 3 Arduino mini sensor clusters that are shown in simplified form on the main diagram.

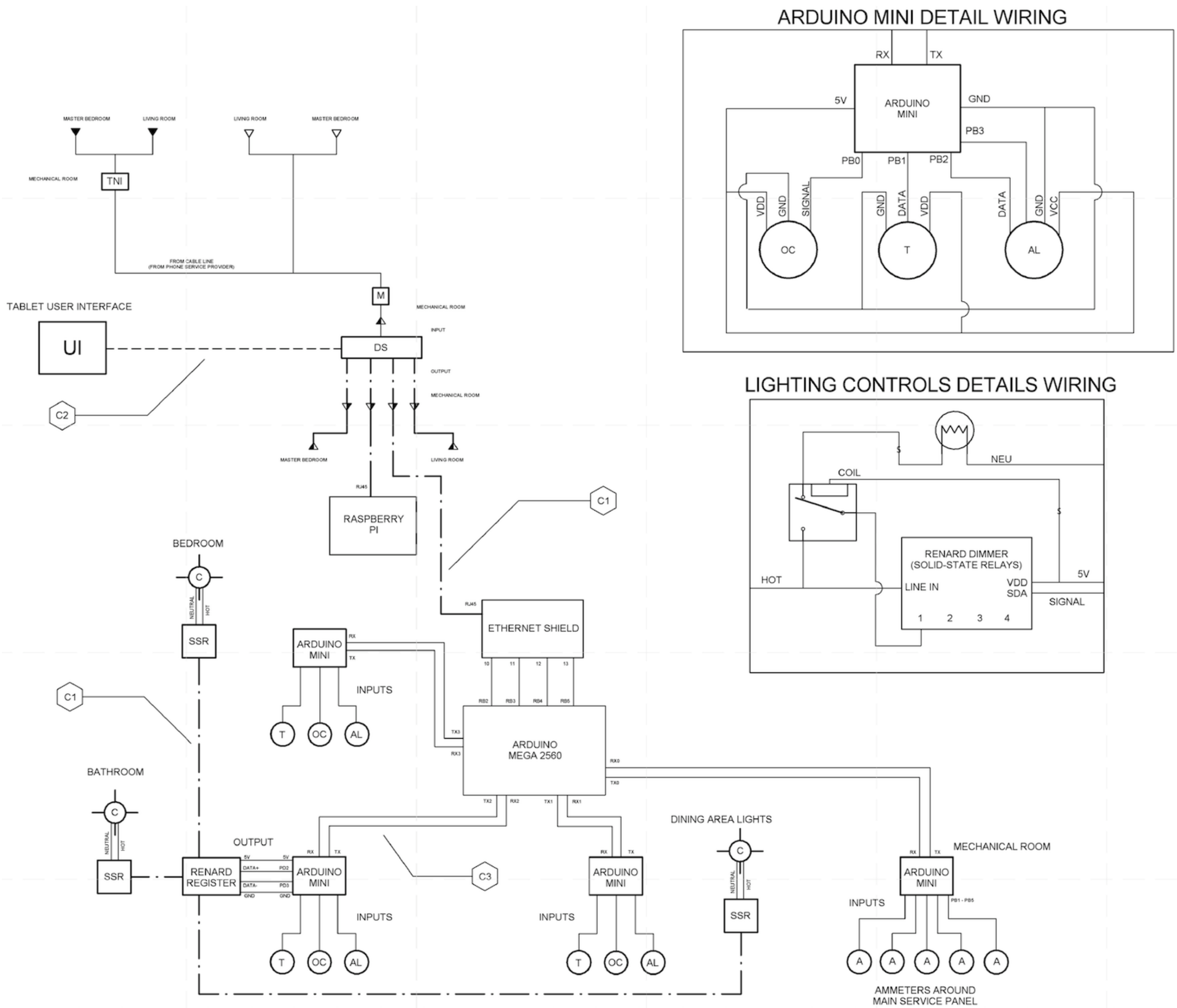


Figure 3. Control System WIring Diagram

Maintenance and Repair Considerations

We designed a system for maintaining manual control even when the control system fails. Shown in Figure 3 above in the box labeled lighting control detail wiring is the circuitry that will be attached to every solid-state relay-controlled light in the house. A non-latching mechanical relay connects the solid-state relays with the lights. Its default position, however, is to connect the lights directly to the hot wire from the main service panel. This ensures that if the control system is switched off the mechanical relay falls into a position where the lights are still switchable from the standard wall switches.

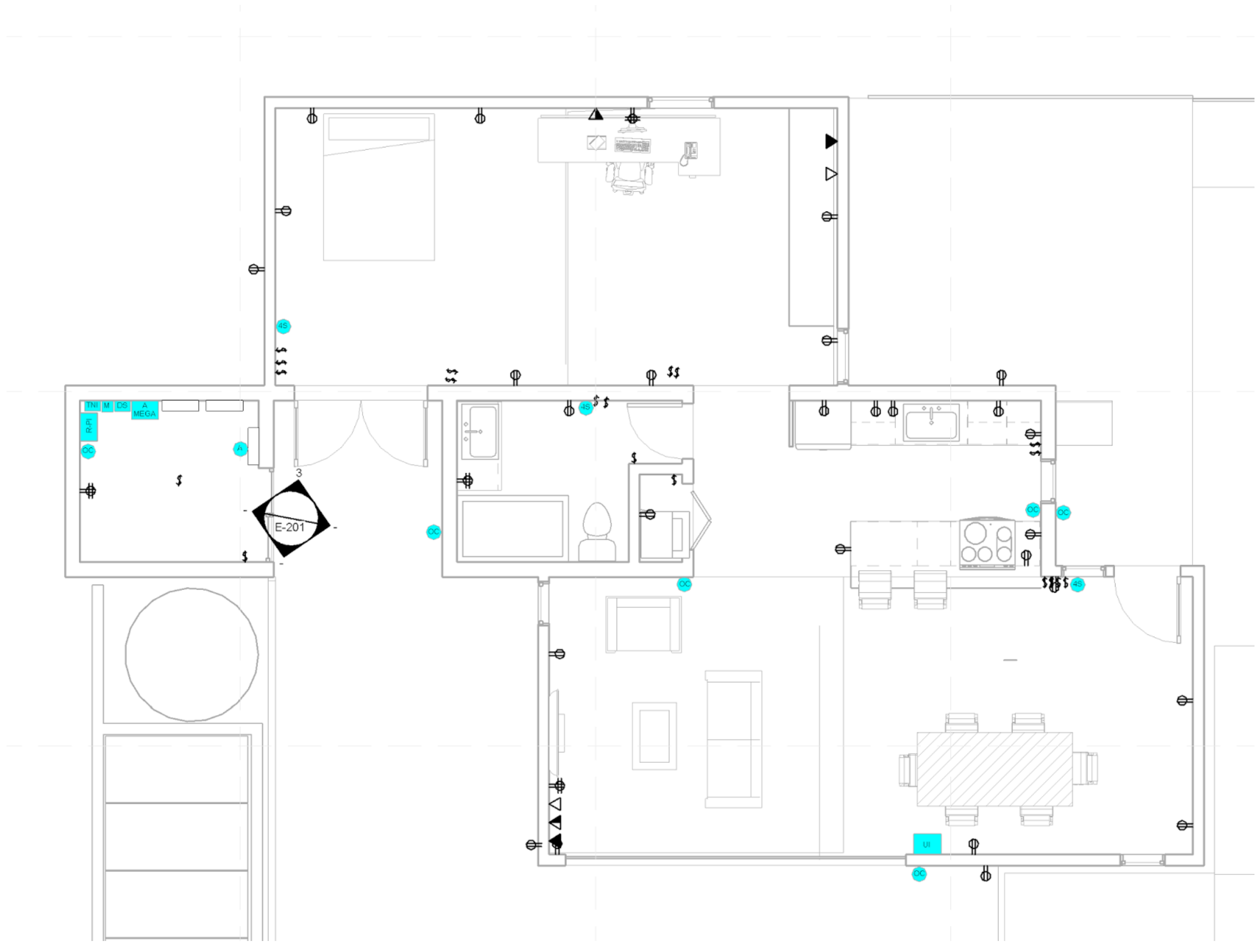


Figure 4. Sensor Placement Diagram

We positioned the sensors so that temperature and light sensors would be central in each room and motion sensors can view the entrances to their respective rooms. There are currently 9 motion sensors, 3 temperature/humidity sensors, and 3 light sensors in the house plan. Figure 4 above details their precise locations.

Chapter 4 Description of Final Design

The instrumentation and controls team shall create a system that will monitor the temperature and humidity and operate the phase change material duct developed by the passive HVAC team. We will work with the electrical engineering team to create an energy monitoring system and with the computer science team to create an app.

With the advice of our advisor Dr. Shollenberger, we decided to scrap our own lighting control system to use an off-the-shelf system instead. We will be installing a Lutron lighting system using HomeWorks QS to control the lights in the house. Testing and refining this system has to wait for the lighting architecture team to finalize their lighting plan, so we will be working on this design over the summer before the competition.

We will use Arduino mini PROs to gather temperature and humidity data. These Arduino mini PROs will communicate with an Arduino MEGA which will serve as a central hub to communicate between Arduinos. One of the Arduino mini PROs will also send signals to control the dampers and fan for the phase change material duct.

Once the Arduino MEGA has the data stored in its memory, it will push the environmental data to the raspberry pi. The raspberry pi will be the meeting point between the computer science team and us. The computer science team will retrieve the data from the raspberry pi to display on the app and to store in their data logger.

See Appendix C for a detailed analysis on the components that we selected. Appendix D contains the data sheets for the selected components.

Our Bill of Materials is located in Appendix E. The total comes out to about $5800, which is much higher than our design limits. This is because of the inclusion of the Lutron system, which we were advised to do by the faculty working on the project. The higher price is OK because it is not too large in comparison to the entire house.

Connectivity and Data Protocols

The connectivity of all parts in the control system is shown in Appendix J. Figure 5 below shows a simplified version of that diagram.

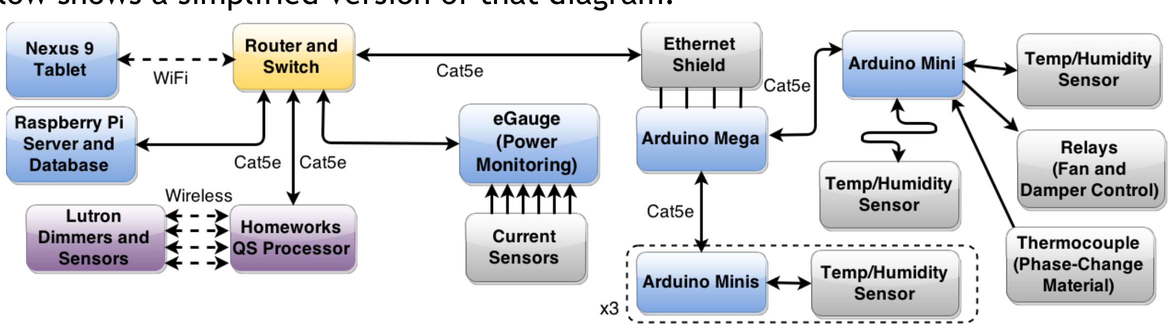


Figure 5. Simplified Control System Connectivity Diagram

The local area network for this project is maintained by an ASUS RT-N66U router and ASUS switch. For purposes of minimizing data corruptions, power draw, expense, and complexity, only one part of the automations system has a wireless link, between the tablet and the Raspberry Pi server. All other connections are Cat5e cable except the very short connections between Arduino Minis and their sensors. The to-scale arrangement of most of these components is shown in Appendix I.

Three Arduino Minis are responsible for reporting the temperature in the Living Room, Bathroom, and Bedroom. The fourth Arduino Mini is responsible for reading the temperature in the kitchen and outside while receiving time of day information from the Mega and deciding whether to open the dampers or not or turn on the fan or not for the Passive HVAC phase-change-material system. The algorithm for this as determined by the Passive HVAC team. All 4 UARTS are being used on the Mega by the 4 Minis, so all debug information must be sent out through the Ethernet shield or through one of the shared UARTS since the 3 Minis that only report readings don't ever receive messages from the Mega.

Analysis Results

An Arduino Mega was chosen for the central data collector and data manager because it has four UART interfaces to easily communicate with other sensor clusters. These clusters use Arduino Mini Pros (5V, 16Mhz) because of their high clock speed and 5V operating voltage like the rest of the system.

The temperature and humidity sensors will be Sparkfun RHT03 Sensors due to their high precision, robustness, error-checking, digital output, and ease of use.

A Raspberry Pi will be used for the CS team's database tool because it is easy for us to send data to and the CS team is confident they will have little trouble setting up a database on it. The connecting cables between Arduinos will be Cat 5e RS-485 transferring bits in 9600b/s serial format. This will allow a distance of up to 1000ft. The microcontrollers will use standard UART serial communication with RS-485 encapsulation because it is a proven protocol for long-distance wired communications. The Arduino Mega will communicate with the Raspberry pi with TCP protocol using an Arduino Ethernet Shield.

For the data switch, we will be using an ASUS RT-N66U Dual-Band Wireless-N900 Gigabit Router. Its range will be plenty for the solar house, even when placed inside the mechanical room. The electrical engineering students will determine the proper wire gauges for our system. AWG 16 will handle the maximum current and is suited for 50ft applications.

We calculated the power consumption of the control system using the datasheets (Appendix D) for each item in Table 3 below. Typical operating voltages and active currents were determined, and the power consumption was calculated with the power equation: $P = IV$. The total power consumption is low compared to our initial budget.

Table 3. Estimated Power Consumption of Control System

Item	Operating Voltage (VDC)	Current Draw (A)	Power per Unit (W)	Quantity	Total Power (W)
Arduino Minis	5	20m	360u	3	1.08m
Raspberry Pi	12.5	0.2	2.5	1	2.5
RGB LEDs	12	583.33m	7	8	56
Samsung Tablet SM-T110N	5	1	5	1	5
DC Solid-State Relays	5	5m	25m	2	50m
Renard Controller	6.3	5	31.5	1	31.5
Temperature sensors	5	1.5m	7.5m	3	22.5m
Ambient Light Sensor	3	48u	144u	5	720u
Occupancy Sensor	3	14u	42u	8	336u
Total	-	-	-	-	102.5

Table 4. Identified Hazards

Description of Hazard	Corrective Actions to Be Taken	Planned Completion Date
120V Source	Insulation, #16 gauge, water-tight enclosures, junction box	August 2015

Table 4 above identifies one hazard of our project which will have to be addressed. All 120V wires will be properly insulated. All electrical junction points will be enclosed in a junction box or coated in liquid electrical tape. All high voltage and low voltage circuit boards will be enclosed in a water-tight enclosure.

Chapter 5 Product Realization

We will install the sensor clusters in multiple 1-gang boxes with a blank wall plate that will cover each gang box. We will laser cut the exact size of the sensor faces out of the wall plate so that only the sensor sticks out of the wall plate as shown in Figure 6 below.

Figure 6. Laser Cut Wall-Plate

Our prototype is the planned design and we are planning on installing our system into the solar house once the house is constructed.

We would like to recommend different design ideas for any future manufacturing of our project. First, we believe that the temperature and humidity sensor can be integrated with the arduino pro minis on a pcb board. If future readers would like to manufacture this product, combining the these two products will be cheaper and will decrease the overall size of the the project.

Another idea would be different wall-plate designs or using another method than using gang-boxes. Instead of using wall plates, future designs can integrate sensors in the walls or with certain objects in the house such as the kitchen counters or bookshelves. We would also recommend a wireless design if users do not want to use our gang-box and wall-plate method. A wireless design would need sensor enclosures that can attach themselves to the wall and operate on batteries. Also a wireless design needs a Wifi-shield for the arduino Mega instead of the ethernet-shield.

Chapter 6 Design Verification

Testing of the system is still in progress and will be until September. The testing we have done so far is described in this section and shown in Appendix F.

After the initial proof-of-concept test we ran as soon as the equipment arrived, we also tested the performance of the sensors inside the gang box shown in Figure 8 on the next page. to see if the enclosure and wall plate would change the operability of the sensor clusters. The performance was identical to the Mini and sensor being outside of the gang box.

For the stress test, we decided to combine the longevity test at the same time to root out as many bugs as possible quickly. Figure 9 two pages below shows the setup for the test. It involved crude connections, wires of very short length (the yellow and red wires on the left) and very long length (the coiled black and blue cables beneath the microcontrollers), and good quality cable and bad quality cable. The black cable was the least expensive Cat 5e cable we could find of 50 foot length. The plastic shielding can be pulled apart easily by pulling with two hands, and the connections we improvised for this test were soldered and duct-taped to achieve the noisiest environment possible to induce errors in data transmission. The blue cable was expensive Belkin Cat 5e cable of 88 feet length. In both cases the data corruption rate was less than 0.5 percent at a transmission rate of two 7-byte bursts every second at 9600 bits/sec for each burst. The longevity test revealed that the Arduino network could reliably send data to the Pi server at 2 data pairs per second for at least 19 continuous days. The actual transmission rate during the competition will be less than 1 data pair every 10 seconds.

Longevity and stress test:
The microcontroller monitoring system lasted 19 days without fail before the experiment was interrupted. During this test the sensor clusters were generating data pairs twice per second each to send to the Mega (10 times faster than the Mega will have to process readings during the competition).

Data Transmission Test:
There was greater than 97.5% accuracy of the transmission of temperature/humidity data coming in from the sensors.

Cross-Talk Test with 120V line:
We verified that the data transmission was read correctly by the Arduino Mega over 88 feet of spliced ethernet cable and 120V live wires running alongside transmission cables.

Power Cycling Test:
The router, server, and microcontrollers all rebooted successfully after the power was cut and reinstated.

Power Draw Test:
The entire microcontroller network runs at 1.35W as evidenced by Figure 7 below.

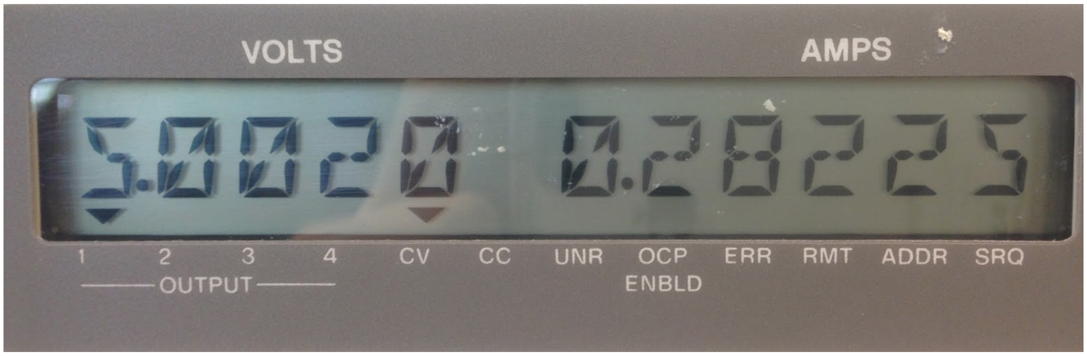


Figure 7. Power Draw Results

Most of the final testing involves confirmation of logic and reliability of the system, which will take place after the system is installed in the house. Our full plan for testing the final prototype is detailed in our Design Verification Plan in Appendix F.

Figure 8. Enclosure Design for Wall-Mounted Sensor Clusters

Figure 9. Longevity and Stress Test

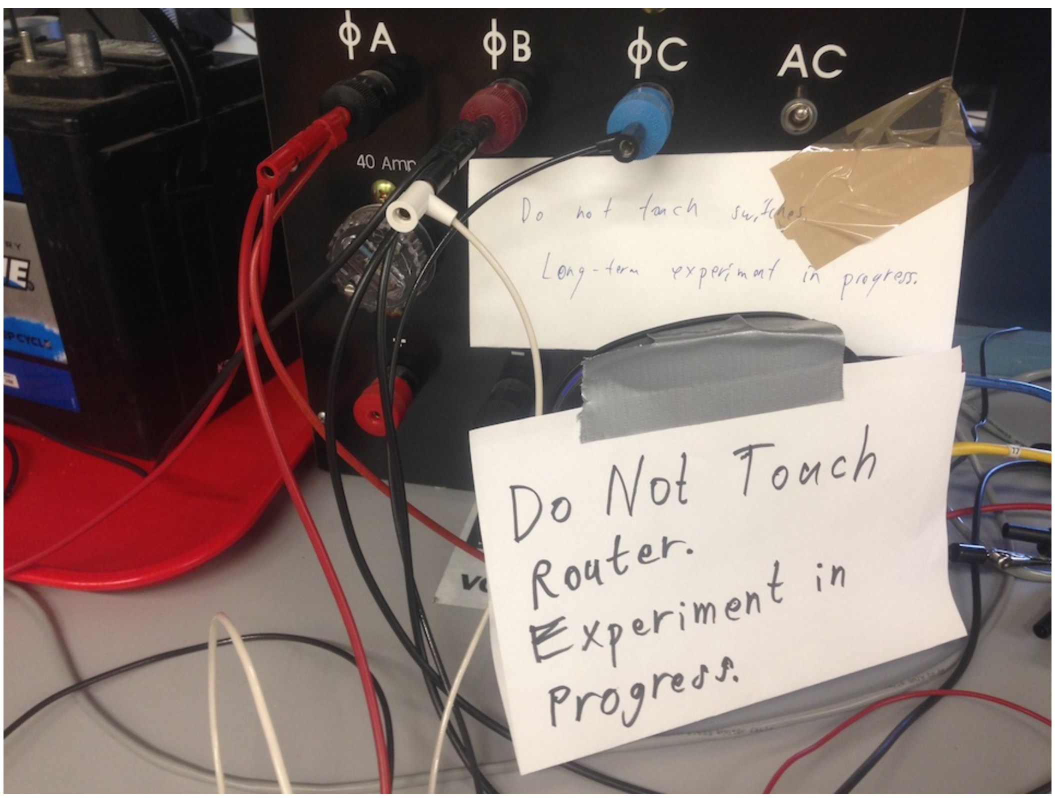


Figure 10. Precautions for long-term experiment in shared lab

Figure 10 above shows some of the signage we erected to protect our equipment from tampering during the potentially 4-week long longevity test. The equipment was never disturbed. Before the signs were put up, the router was unplugged occasionally, disrupting our test.

Figure 11. Current Loops Measuring Energy Usage

Figure 12. eGauge System Used to Monitor Energy Usage

Chapter 7 Conclusions and Recommendations

The instrumentations and controls engineering team designed a system that will monitor temperature and humidity levels and control the Passive HVAC phase-change material system using ordinary microcontrollers, sensors, wire, and enclosures.

After collecting environmental data, the Arduino Mini Pros need to communicate to a central hub which we chose to be an Arduino Mega. The communication between the Arduino Mini Pros and the Arduino Mega is possible with standard Serial protocol and Cat5e cable at 88 feet of wire or more. The custom protocol we designed for this works perfectly at speeds of up to 2 data pairs (readings) per second. The protocol between the Mega and the CS team's server is HTTP formatted with help from their team.

The Lutron lighting control system is easy to work with, easy to reprogram, intuitive to design, and well-known in industry. It will make an excellent, stable alternative to the proprietary system we attempted to design.

The Arduino network uses 1.38W of power continuously. The 5 simultaneously running programs plus the Raspberry Pi's server and database run well together for at least 19 days at maximum transmission rate. The system shows no instability at the regular rate of 1 transmission per 10 seconds.

From now until September, we will continue to improve the performance of the control system and bring Cal Poly's chances of winning the Solar Decathlon ever higher. This project is quite useful in understanding how other successful home-automation companies got their start. Hopefully a system like this one will assist future competition teams in engineering even better proprietary control systems developed right here at Cal Poly San Luis Obispo.

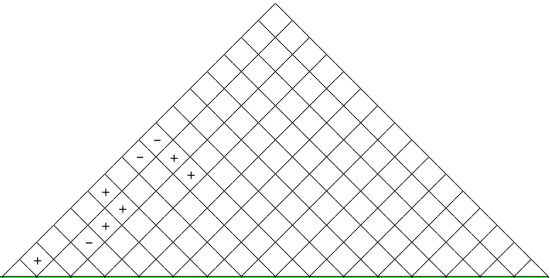
QFD: House of Quality
Project: Solor Decathlon
Revision: 1.00
Team: Instrumentation and Controls
Date: 14 Oct 2014

Appendix A: House of Quality

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



WHO: Customers

Row #	Weight Chart	Relative Weight	DOE	Humanity	Client	Solar Decathlon Team	Maximum Relationship	WHAT: Customer Requirements (explicit & implicit)
1		20%	15	15	25	25	9	Cheap
2		16%	25	20	12	8	9	Energy Efficient
3		15%	12	25	6	15	9	Sustainable
4		10%	4	10	20	4	3	Comfortable
5		10%	6	12	8	12	3	Modern
6		8%	10	6	10	6	9	Visually Appealing
7		10%	8	8	15	10	9	Easy to Use
8		12%	20	4	4	20	9	Marketable
9		0%						
10		0%						
11		0%						
12		0%						
13		0%						
14		0%						
15		0%						
16		0%						

HOW: Engineering Specifications

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction of Improvement	▲	▼	◇													
WHAT \ HOW	Construction Cost	Cost of Parts	Power Draw of Control Systems	Min operating Temperature	Max Operating Temperature	Long Life	Consistent Lighting (Max % Change in Ambient Light)	Max Wall Footprint Area of Sensors	Number of Controls							
Cheap	●	●		▽	▽											
Energy Efficient			●													
Sustainable			▽	●	●	●										
Comfortable							○									
Modern							○	▽	▽							
Visually Appealing							○	●	○							
Easy to Use				▽	▽				●							
Marketable	●			▽	▽	○		▽	▽							
HOW MUCH: Target	$1,000	$1,000	400W	-20°F	200°F	30 years	20%	6 in^2	4							
Max Relationship	9	9	9	9	9	9	3	9	9							
Technical Importance Rating	288	180	160.75	172.75	172.75	166.5	81	93.5	137.75							
Relative Weight	20%	12%	11%	12%	12%	11%	6%	6%	9%							
Weight Chart																
Our Instrumentation and Controls																
UNLV Solar House 2013																
Team Austria 2013																
Team Germany 2009																
Team Ontario 2013																

NOW: Current Product Assesment - Customer Requirements

Row #	Our Instrumentation and Controls	UNLV Solar House 2013	Team Austria 2013	Team Germany 2009	Team Ontario 2013
1	5	5	4	1	5
2	5	5	5	3	4
3	4	5	4	5	5
4	5	5	5	4	5
5	4	3	5	4	5
6	3	3	4	3	3
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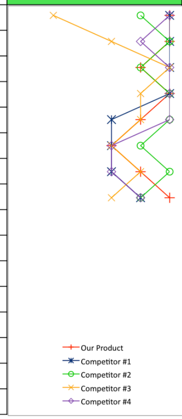
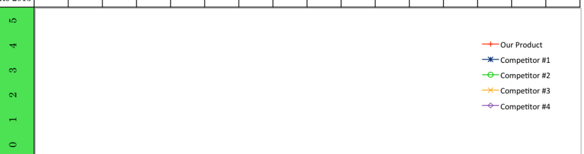


Current Product Assesment - Engineering Specifications



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix B: References

References

Closed Loop Integrated Lighting and Daylighting Control for Low
Energy Buildings. Satyen Mukherjee, et. al. Philips Research North America.
http://w.energytaxincentives.org/files/proceedings/2010/data/papers/2204.pdf

University of Maryland 2011 Solar Decathlon Construction Drawings.
http://www.solardecathlon.gov/past/2011/pdfs/umd_cd.pdf

California 2013 Building Energy Efficiency Standards: Title 24
http://www.energy.ca.gov/title24/2013standards/index.html

Appendix C Detailed Design Analysis

Central Data Collector and Manager - Arduino Mega

Ruling out other systems:

1. WinkHub
    - Overkill
    - Capable of controlling entire home automation system
    - Interfaceable with other commercial home automations systems
    - Not capable of interfacing with our custom app
        - Commercial app already established
        - Exact format of their data packets not known and might in fact be secret proprietary info
    - Brand new platform we would have to learn
2. Raspberry Pi alone
    - Does not easily interface with many incoming serial interfaces
        - Build for graphical interface and operating system capability
        - Digital I/O pins don't have more than one hardware serial interface (with a received-data cache)
    - Brand new platform we would have to learn
    - Requires huge amount of collaboration with the CS team
        - They would be building their database on the same Raspberry Pi
        - The two programs would be running simultaneously and data collisions would have to be taken into account
3. Arduino Uno
    - Does not easily interface with many incoming serial interfaces
        - Digital I/O pins don't have more than one hardware serial interface (with a received-data cache)
        - Software serial interfaces have to be continually checked and is very inefficient

Validation of our choice (Arduino Mega):

1. 4 UARTs
    a. Four hardware-buffered inputs that can all receive data simultaneously
    b. Software doesn't need to worry about collecting the bits
    c. Data is held in buffer until software can process the packet
2. Same platform
    a. Easy to transfer code developed on any of the arduinos to to the central controller and vise versa
    b. Platform already familiar to us
    c. Easy communication between two arduino platforms
3. Same voltage level
    a. Whole system will be based on 5V and the Mega uses 5V also
    b. Single power supply for everything
4. Ethernet shield
    a. Ethernet shield and ethernet library easily support TCP and UDP
    b. Designed to work with Arduino Mega

    c. Secure mechanical and electrical connection to microcontroller
    d. Transmits up to 100 feet with a wired connection to data switch
5. 16 MHz Clock
    a. More than fast enough to read data from 4 arduino modules sending 10-byte packets at 1200 bytes per second, 1-3 packets per second
    b. Thousands of free clock cycles in between reading Arduino Mini packets to send out TCP packets to Pi database

Sensor cluster microcontroller - Arduino Mini Pro 5V 16MHz

The Arduino Pro Mini is the preferred microcontroller because it is based on the ATmega168 which is similar to the central data collector and manager(Arduino MEGA). It uses ATmega328p which is a very familiar microcontroller for our team (same as Arduino UNO).
Some desirable features are:

1. Operates at 3.3 or 5V
2. 14 digital I/O pins (6 can output Pulse-Width Modulated signals)
3. 8 analog input pins
4. DC Current per I/O Pin = 40mA
5. 16 MHz Clock
6. Powered with an FTDI cable or breakout board connected to its six pin header, or with a regulated 3.3V or 5V supply on the Vcc pin.
7. Small Package: 0.7” x 1.3”

Light Sensor - Photodiode

The ambient light sensor that the instrumentations and controls team will be using is the SFH 2430 photodiode. This sensor covers the spectral range that the human eye is sensitive to. It’s main features from the datasheet are:

1. Spectral sensitivity adapted to human eye sensitivity (V_λ)
2. Low temperature coefficient of spectral sensitivity
3. High linearity
4. DIL plastic package with high packing density.

The photodiode’s main parameter that will be used to measure the lux is the spectral sensitivity parameter. The SFH 2430 sensor has a standard value of 6.3 nA/lux. This means that 6.3nA will be emitted in proportion to the light that shines on the face of the photodiode.

The only problem for the instrumentation and controls team is that the microcontrollers are not sensitive to small(nA) changes in current. Microcontrollers prefer dramatic changes in voltage on its pins. Therefore, students must design a current to frequency converter which will convert the current produced by the photodiode to be proportional to a specific frequency at a readable voltage. Before the current-to-frequency converter is designed, designers must create a current amplifier to create a proportional current that the current-to-frequency converter can detect as shown in Figure 13 below.

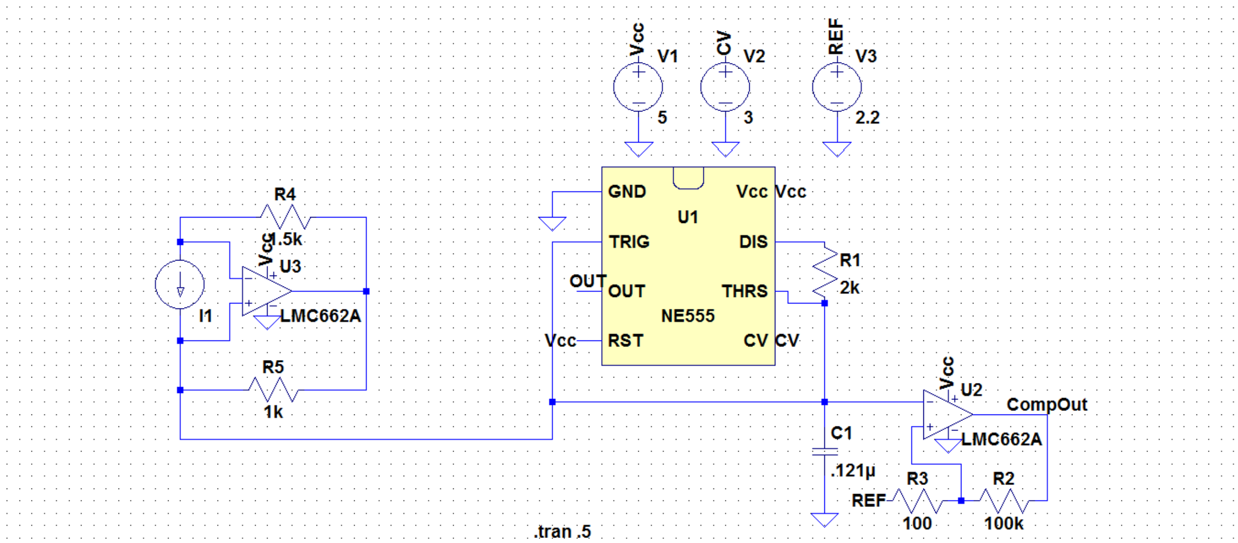


Figure 13. Current to Frequency Converter

The output of this circuit is shown in Figure 14 below.

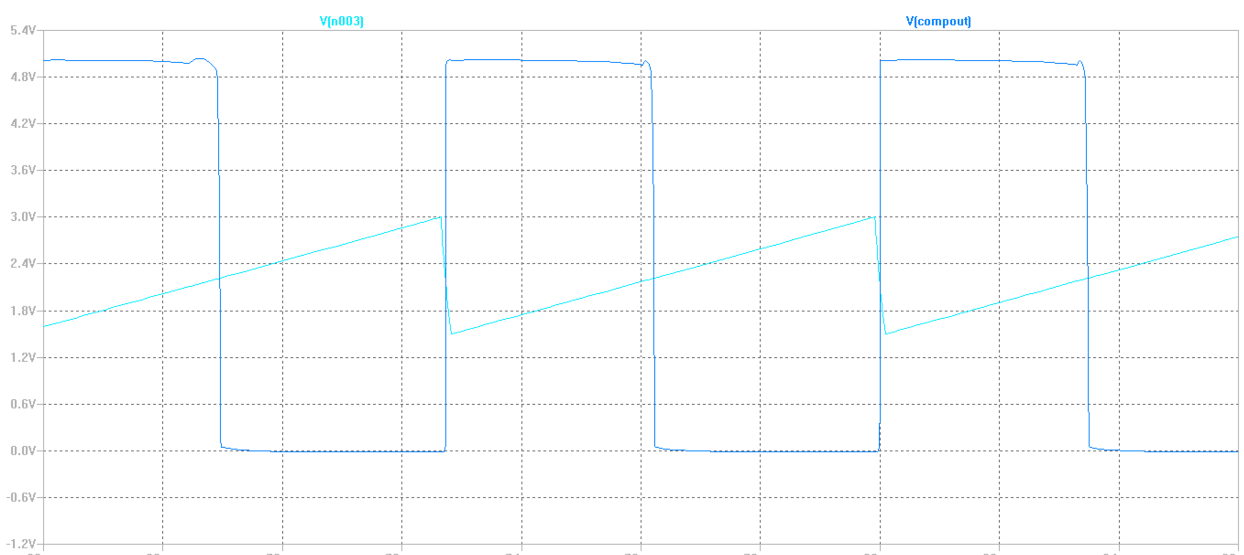


Figure 14. Output of the Current to Frequency Converter

The output of the current to frequency converter goes rail-to-rail which makes it easier for the arduino to detect when the output transitions between low and high.

Light Detection Flow Chart

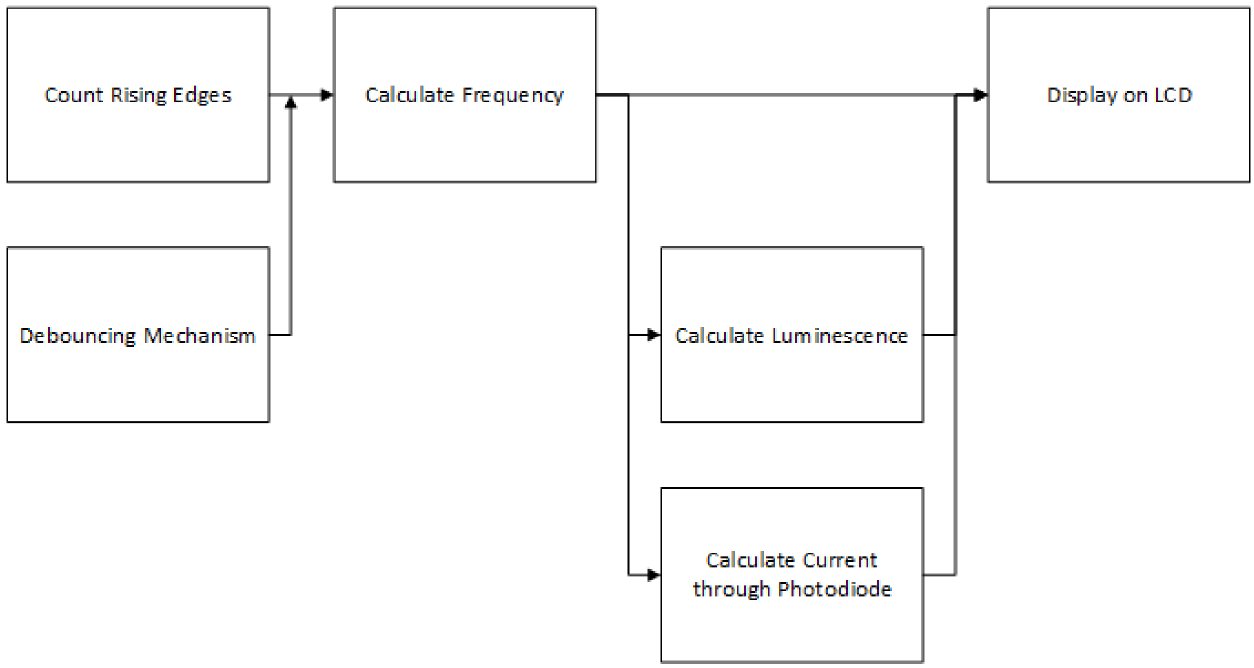


Figure 15. Reading Ambient Light Level Algorithm

Motion Sensor - PIR binary motion sensor

The PIR (Passive Infra-Red) sensor detects motion by measuring sudden changes in infrared levels generated by surrounding objects. The PIR sensor takes a snapshot of the infrared levels in the room and outputs high on its output pin when a sudden change in infrared levels occur. It's features include:

1. Detection range up to 15ft on short mode and 30ft away on long mode.
2. A jumper selects between the two range modes.
3. Easy interface with any microcontroller
4. Small size makes it easy to conceal
5. Onboard LEDs light up when motion is detected
6. Supply voltage: 3 to 6V

A disadvantage to this sensor is that it is for indoor use only. Outside use will negatively affect the stability of the device. Another disadvantage is that it takes approximately 40 seconds for the sensor to calibrate.

Temperature / Humidity Sensor - Sparkfun RHT03 Sensor

1. High precision
    a. ± 0.5^{0}C accuracy
    b. ± 2% relative humidity accuracy
2. Robust
    a. Time tested. Capable of running continuously confirmed by customer reviews. https://www.sparkfun.com/products/10167
3. Error-Checking
    a. If the data transmission arrived without error, checksum should be: Checksum = 8-bit integral RH data + 8 bit integral T data +8 bit decimal T data
    b. This value is compared to the actual checksum at the end of the 40-bit packet transmission.
4. Digital output
    a. Fixed precision based on an exclusive digital signal
    b. Data received from this sensor can be reproduced and transmitted exactly as the original data was with no loss of precision.
    c. No analog hardware to calibrate, no reference voltages to skew the data
5. Simple to use
    a. Long read time
        i. Allows microcontroller hardware interrupts to discern pulse width while other calculations are running
        ii. Less than one second between the start of each read, more than we need for slowly changing room temperatures
    b. Well-defined protocol of long and short pulse widths

Database tool - Raspberry Pi with websockets

CS decided on Raspberry Pi for their own reasons (not our analysis)

1. Supports Linux Databases
2. Supports web sockets

Data Switch - ASUS RT-N66U Dual-Band Wireless-N900 Gigabit Router

1. 100+ product reviews specifically referencing the the range of this router in household applications
    a. 2500+ square foot houses have no problem receiving 75% or more of a full signal strength from anywhere on the premises, including outside and passing through 3 walls
2. Actual calculation for verifying Wifi signal strength for our application cannot be done without measuring the dB loss through our actual walls and knowing the receiving antenna's sensitivity in dB.
3. Very rough calculation based on assumptions shown in Appendix H.

Cabling between Arduinos - RS-485 over Cat 5e cables

Two UART to RS-485 converters will be used to change the native arduino UART serial protocol to a differential protocol that is not nearly as sensitive to capacitive noise and lag as the UART protocol.

1. Reliable
    a. RS-485 is a proven protocol that is designed to work with serial data over long-wired distance
    b. Errors are almost non-existent for distances less than 1000ft because the protocol is not sensitive to the capacitance of the transmission wires.
2. Long distance support
    a. RS-485 works up to 1.2 km for a single non-repeated connection between microcontrollers
    b. For less than 1000 feet distances, RS-485 supports speeds greater than 16MHz, the speed of the arduino's microprocessor.
3. Twisted-pair cabling
    a. Standard Cat 5e cabling is the standard for RS-485 transmission
    b. Provides noise protection for up to 100ft in standard household 120V noise environments without needing a repeater.
4. Hardware process
    a. All the conversion from serial UART to RS-485 is done by the MAX485 ship on the RS-485 breakout board.
    b. Conversion back to serial UART is done on the receiving end with another breakout board.
    c. No wasted microcontroller clock cycles converting to a different format.

Between Arduino and Raspberry Pi - TCP

1. Well-established protocol
    a. TCP is the standard internet protocol for sending generic data in 1200 byte chunks.
    b. Protocol is very well defined and tested and well known by nearly all internet-connected hardware
2. Error-checking
    a. Built-in error checking for all transmissions
    b. Hardware or software process for re-sending the data if it was mis-transmitted.
3. Easy to send to database
    a. Simply specify the websocket the Arduino establishes with the Raspberry Pi database and the port number of the receiving machine and off goes the data.
    b. Robust, thoroughly-tested library for handling all data transmissions comes with the shield.
4. Hardware process

a. The Arduino ethernet shield handles the assembly of the TCP/IP/Ethernet stack given the data.
b. Only 3 commands in the Arduino code for setting up the sending of the data to a specific web socket and the shield hardware takes take of the rest.

Appendix D: Data Sheets

Datasheets

Photodiode: http://www.osram-os.com/Graphics/XPic3/00083291_0.pdf

Motion sensor: http://www.jameco.com/Jameco/Products/ProdDS/2082927.pdf

Temperature/Humidity Sensor:
http://dlnmh9ip6v2uc.cloudfront.net/datasheets/Sensors/Weather/RHT03.pdf

Arduino Mini: http://www.arduino.cc/en/Main/ArduinoBoardMini

Arduino Mega: http://arduino.cc/en/Main/ArduinoBoardMega2560

RS-485 Breakout board:
https://www.sparkfun.com/datasheets/Components/General/sp3485CN-LTR.pdf

Router: http://www.asus.com/Networking/RTN66U/specifications/

Appendix E - Bill of Materials

NO.	QTY.	Cost	Unit Total	ITEM	DESCRIPTION	LOCATION	MANUFACTURER	VENDOR	PART NUMBER
1	5	$9.95	$49.75	HUMIDITY - TEMERATURE SENSOR	Measures the outside temperature and relays that information to the controler and the home owner.	NORTH OUTSIDE WALL, BEDROOM, BATHROOM, LIVING ROOM	MAXDETECT	sparkfun.com	SEN-10167
2	1	$45.99	$45.99	ARDUINO MEGA 2560 R3	Recieves input from the sensors and home owner's commands and controls the ambient light and color temperature.	MECHANICAL ROOM	ARDUINO	sparkfun.com	DEV-11061
3	4	$9.95	$39.80	ARDUINO MINI PRO	Collects sensor data and feeds the information to the Arduino Mega central controller.	BEDROOM, BATHROOM, LIVING ROOM, KITCHEN	ARDUINO	sparkfun.com	DEV-11113
4	15	$9.95	$149.25	AMMETER (ON-WIRE)	Coil of wire that is installed around the wires of the main service panel. Measures current and can be used to calculate power usage on each major circuit of the house.	MECHANICAL ROOM	ECHUN	sparkfun.com	SEN-11005
5	1	$435.00	$435.00	NEXUS 9 TABLET	The user interface which will display all information about the sensors and allow the user to make changes to the controls. The tablet will host the app as well.	LIVING ROOM SOUTH WALL	SAMSUNG	samsung.com	SM-T530NZWAXAR
6	1	$35.00	$35.00	RASPBERRY PI - B+	These downlights contain bright red, green, and blue LEDs that can blend into any color including white using our control system and some solid-state relays.	BEDROOM, BATHROOM, LIVING ROOM	RASPBERRY PI FOUNDATION	alliedelec.com	70377493
7	4	$4.95	$19.80	SINGLE-THROW AC SOLID-STATE RELAYS	Control the fan and dampers directly from an Arduino Mini receiving time data	PASSIVE HVAC SYSTEM SPACE	SHZHE	amazon.com	B00P7Q7S9I
8	1	$110.00	$110.00	ASUS RT-N66U WIRELESS ROUTER	Switches data from modem to 4 other network cables providing internet to both bedrooms and the living room. Provides wireless networks for whole house and enables communication between tablet and control system.	MECHANICAL ROOM	ASUS	newegg.com	N82E16833320091
9	1	$35.00	$35.00	ASUS GX-D1051 DATA SWITCH	Provides extra wired network connections for eGauge, Mega, Pi, and others	MECHANICAL ROOM	ASUS	newegg.com	N82E16833320160
10	30	$1.05	$31.50	FEMALE CAT 5E KEYSTONES	Standard sources of wired internet for the bedrooms and living room. Also the connection type for all communicatoins between microcontroller modules	BEDROOMS, LIVING ROOM, MECHANICAL ROOM	MONOPRICE	monoprice.com	310
11	30	$0.10	$3.00	MALE CAT 5E CONNECTORS	Connection type for all communicatoins between microcontroller modules	BEDROOMS, LIVING ROOM, MECHANICAL ROOM	MONOPRICE	monoprice.com	7300
12	1	$6.00	$6.00	CHANGEOVER SWITCH	For switching the conrol system into manual control	MECHANICAL ROOM	AMICO	amazon.com	B00D7IMQYU
13	1	$5.90	$5.90	SOLDERABLE PROTOTYPE BOARD	For securing all connections to the Mega, Minis, and changover switch	MECHANICAL ROOM	BOUSBOARD PROTOTYPE SYSTEMS	amazon.com	B0040Z3012
14	1	$68.99	$68.99	CAT 5E NETWORK CABLE 500 FEET	Connects data receptacles to data switch.	UNDER CORE FLOOR	BELKIN	newegg.com	N82E16812314931
15	1	$4,700.00	$4,700.00	LUTRON CONTROL SYSTEM	Controls lights only, interfaces with Server on Raspberry Pi, programmed by Controls team	MECHANICAL ROOM, and throughout the house	LUTRON	pasolumination.com	N/A
16	5	$1.57	$7.85	SINGLE GANG BOX + FACEPLATE	Holds the sensors and arduino mini PROs.	BEDROOMS, LIVING ROOM, MECHANICAL ROOM	LEVITON	homedepot.com	R52-88014-W
17	1	$45.95	$45.95	ETHERNET SHIELD	For communicating with the Arduino Mega	MECHANICAL ROOM	ARDUINO	sparkfun.com	DEV-09026
		TOTAL	$5,788.78						

Appendix F - Design Verification Plan & Results

Report Date 5 June 2015 **Sponsor** Solar Cal Poly Component/Assembly REPORTING ENGINEER:

TEST PLAN										TEST REPORT			
						SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
Item No.	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Cost of Parts	Total up cost of all parts purchased and donated \ Verify total is less than $6000	Total cost < $6000	Timothy Ambrose	DV	1	B	3/29/15	3/29/15	$4700+	1	0	
2	Power Draw of Control Systems	Measure power consumption of controllers \ Display on USART terminal screen \ Display on app	Total power of digital logic systems < 200W	Mateo Begue	PV	1	C	4/5/15	4/5/15	0.277mA (1.385W)	3	0	
3	Min Operating Temperature	Test controller in fridge and freezer \ Monitor performance	Behavior unchanged, < 50% slower operations	Andrew Elliott	PV	1	C	4/6/15	6/4/15				
4	Max Operating Temperature	Test controller in direct sunlight \ Monitor performance	Behavior unchanged, < 50% slower operations	Andrew Elliott	PV	1	C	4/7/15	4/7/15				
5	Longevity	Have controller continuously run program for weeks (months if possible) \ Monitor performance change over long period of time	Behavior unchanged, < 50% slower operations	Timothy Ambrose	PV	1	C	4/8/15	5/8/15	19 days so far	0	8	
6	Consistent Lighting	Set desired light level \ Set controller to maintain that level \ Measure ambient light level in room \ Compare with desired light level \ Change external light source \ Measure resulting change in artificial light levels	< 5% error in desired lux, except when lights are 100% on or off	Mateo Begue	PV	3	C	6/1/15	6/5/15				
7	Max Wall Footprint Area of Sensors	Measure footprint of enclosed sensors \ Compare with desired max footprint	< 8 sq. in.	Andrew Elliott	DV	1	B	2/1/15	2/5/15	14 sq inches	1	0	
8	Number of Controls	Count the number of steps required for user to perform desired control operation \ Count the number of controls available to user on each screen \ Time how long it takes a new user to find a particular setting or control in the app	< 4 steps \ < 7 controls/screen \ < 40 sec	Timothy Ambrose	DV	1	B	2/1/15	2/5/15				
9	User Interface / Control	Click button on app \ Verify action results from button push (lights dim or switch on/off) \ Measure response time of controllers carrying out the action the user requested \ Verify manual control switch takes away control from controller and leaves mechanical switches in complete control of light circuits	Action results after button push >95% of time \ < 2 sec \ Manual control achieved 100% of time	Mateo Begue	PV	1	C	5/9/15	5/9/15				
10		Walk by occupancy sensor \ Verify controller acknowledges person walking near occupancy sensor	Acknowledges motion > 95% accuracy	Timothy Ambrose	PV	3	C	4/8/15	5/8/15				
11		Walk by two successive occupancy sensors (walk into/out of room) \ Verify controller increases count of people in room	Miscounts people < 5% of time	Andrew Elliott	PV	3	C	4/8/15	5/8/15				
12		Attempt to confuse controller with multiple people walking by multiple sensors \ Take note of problems and logic errors \ Add contingencies into algorithm	Miscounts people < 10% of time	Mateo Begue	PV	3	C	4/8/15	5/8/15				
15		Read data from ambient light sensor using Arduino \ Verify ambient light sensor data is accurate with handheld light sensor \ Confirm reading with precision multimeter	< 5% deviation once light level stabilizes \ < 10% difference from desired light level	Timothy Ambrose	PV	3	C	4/8/15	5/8/15				
16	Logic Confirmation	Read data from temperature/humidity sensor using Arduino \ Verify sensor data is accurate with calibrated thermometer/hygrometer \ Confirm reading on sensor with oscilloscope	Displayed temperature and humidity <5% off from measurement	Andrew Elliott	PV	3	C	4/8/15	5/8/15	Pass	2	0	T +/- 1.36% H +/- 11.5%
17		Verify controller will shut off lights after 15 minutes of no movement and 0 people counted	Lights shut off successfully 100% of the time	Mateo Begue	PV	3	C	4/8/15	5/8/15				
18		Verify controller will shut off lights after 90 minutes of no movement and 1+ people counted	Lights shut off successfully 100% of the time	Timothy Ambrose	PV	3	C	4/8/15	5/8/15				
19		Verify high voltage circuit of lights remains closed when controller disconnected	Light switches work without the controller 100% of time	Andrew Elliott	PV	3	C	4/8/15	5/8/15				
20		Read current data with Arduino \ Calculate and display power (on terminal and app) \ Use commercial power meter or multimeter to confirm measurement	Displayed power <5% off from measurement	Mateo Begue	PV	3	C	4/8/15	5/8/15				
21		Verify minimal packet corruption over lengthy data wires \ Add noise to environment to test packet transmission	< 5% of data corrupted \ 0% data lost	Timothy Ambrose	PV	1	C	4/8/15	5/8/15	3% of data corrupted	5	0	Tested with 50ft, cheap Cat5 cable Tested with 88ft

Appendix G: Gantt Chart

Instrumentation and Controls Engineering

Solar CalPoly

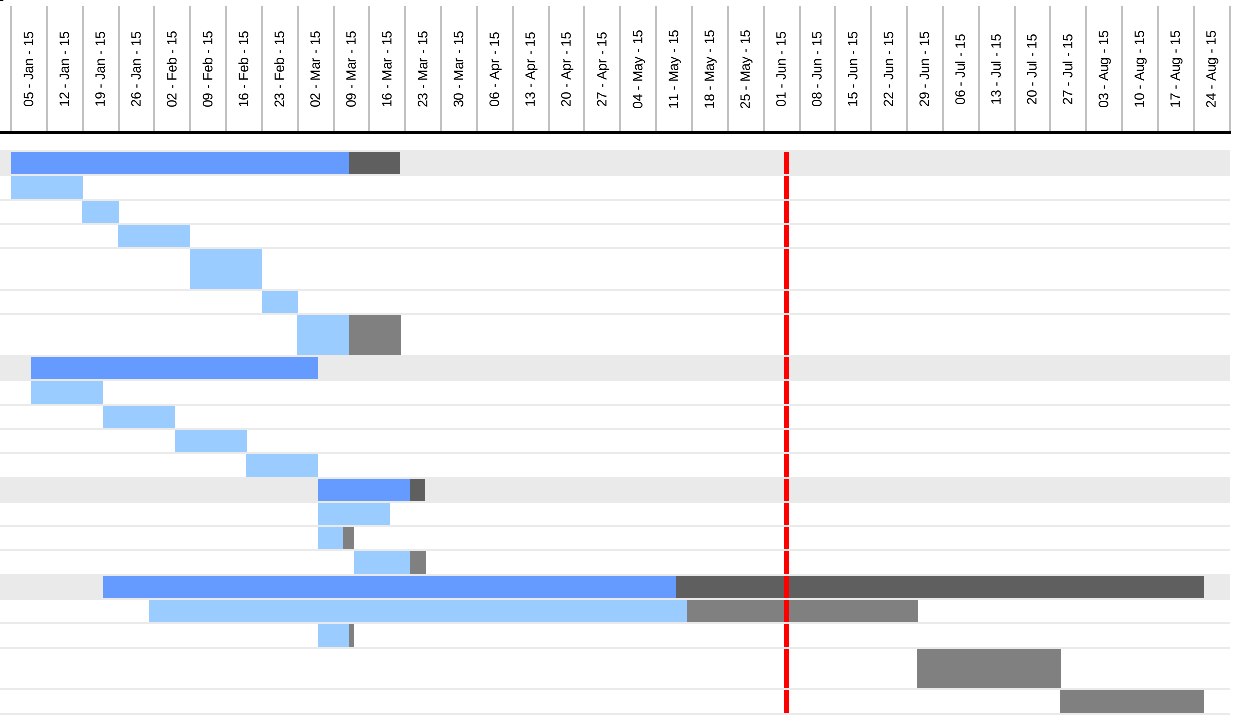
Project Lead: ____________

Today's Date: 6/5/2015 (Fri) (vertical red line)

Start Date: 1/5/2015 (Mon)

First Day of Week (Sun=1): 2

WBS	Tasks	Task Lead	Start	End	Duration (Days)	% Complete	Working Days	Days Complete	Days Remaining
1	Design		1/05/15	3/22/15	76	87%	55	66	10
1.1	Explore Data Protocols		1/05/15	1/19/15	14	100%	11	14	0
1.2	Choose Data Protocol		1/19/15	1/26/15	7	100%	6	7	0
1.3	Code Data Passing		1/26/15	2/09/15	14	100%	11	14	0
1.4	Test and Revise Communications		2/09/15	2/23/15	14	100%	11	14	0
1.5	Stress Testing		2/23/15	3/02/15	7	100%	6	7	0
1.6	Fancy Data Protection and Optimization		3/02/15	3/22/15	20	50%	15	10	10
2	Proof of Concept		1/09/15	3/06/15	56	100%	41	56	0
2.1	Temperature Sensor		1/09/15	1/23/15	14	100%	11	14	0
2.2	Arduino Mini		1/23/15	2/06/15	14	100%	11	14	0
2.3	Arduino Mega		2/06/15	2/20/15	14	100%	11	14	0
2.4	Communication		2/20/15	3/06/15	14	100%	11	14	0
3	Implementation		3/06/15	3/27/15	21	88%	16	18	3
3.1	App communication		3/06/15	3/20/15	14	100%	11	14	0
3.2	Lutron Lighting Design		3/06/15	3/13/15	7	80%	6	5	2
3.3	Lighting Control Design		3/13/15	3/27/15	14	80%	11	11	3
4	Build and Test		1/23/15	8/26/15	215	52%	154	112	103
4.2	App Development		2/01/15	7/01/15	150	70%	108	105	45
4.3	Order Parts		3/06/15	3/13/15	7	95%	6	6	1
4.4	Build and Test All Together		7/01/15	7/29/15	28	0%	21	0	28
4.5	Fine Tuning		7/29/15	8/26/15	28	0%	21	0	28



Appendix H: Hand Calculations

Rough Wifi Strength / Range Calculation

$$\text{range} = \frac{10^{[P_t + g_t + g_r + P_r]/20}}{41.88 * f_{MHz}}$$

WCS = worst case scenario

P_t = transmission power

P_r = receiver required power (sensitivity)

g_t = transmitting antenna gain

g_r = receiving antenna gain

ASUS RT-N66U Router

P_t = 17 - 26 dBm
$g_t \approx$ 2 dBi (average external antenna WCS)
f = 2.442 GHz

assumed receiver characteristics based on average wifi internal antennas

$P_r \approx$ 66 dB (IEEE 802.11n)

$g_r \approx$ 2 dBi (average)

$$r = \frac{10^{\wedge}[17+2+2+66]/20}{41.88 * 2442_{[MHz]}} = 218.9 \text{ m}$$

loss through gypsum board insulated walls (attenuation) = 4 dB $\approx \frac{1}{3}$ of original signal strength

n walls => 1/9 of original strength

Signal Range continued

$$\frac{218.9\,m}{9} = 24.3\,m = \boxed{79.8\,ft}$$

= more than the length of the house WCS

Appendix I: Detailed Diagram of Control Panel

Appendix J: Detailed Connectivity Diagram for Control System