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Mechatronics Application to Solar Tracking

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Purdue University West Lafayette, Indiana

College of Technology

Mechatronic Application to Solar Tracking

In partial fulfillment of the requirements for the
Degree of Master of Science in Technology

A Directed Project Proposal

By

Danny Rodriguez

4/14/2011

Committee Member	**Approval Signature**	**Date**
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College of Technology
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Title of Directed Project: Mechatronics Application to Solar Tracking

For the degree of Master of Science in Technology

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1. Executive Summary

The purpose of this was to design and implement a two-axis solar tracking system utilizing the National Instruments C-Rio real time controller. In order to accomplish this a prototype was modeled in CAD. This prototype used two 12 V DC motors to change a solar panel's rotation and tilt based on feedback data from three cadmium sulfide photoresistors. This configuration was chosen for its ability to create both a left-right rotational and an up/down tilt differential. In Addition this approach uses National Instruments Labview to control a solar tracking system. Using Labview add uniqueness to this project by adding a graphical programming approach instead of conventional text based coding.

Solar collection data was taken for seven days. During the energy collection performed on the first day and the second day the sensitivity was calibrated for outdoor conditions. The results have shown that a 28% increase in energy collected with solar tracking, however due to the energy demands of C-Rio controller and motors the net energy gains were less than a stationary collector.

This project has resulted in a working solar tracking prototype. With a few design modifications an upgrade to this system may prove useful in future research. With the growing complexity of technology, interest in mechatronics will continue to develop requiring further research will be necessary. Therefore, this project provides Purdue University with demonstration prototype in the up and coming field of mechatronics.

2. INTRODUCTION

Modern society is dependent on readily available electrical power. Without a stable source of energy, the continued prosperity of the human population cannot be maintained. As the population of humans grows, so does the demand for electrical energy. As the world enters the new century, the depletion of carbon based fossil fuels is becoming more problematic. In order to prevent catastrophic energy depletion, alternative power sources must be realized. The use of fossil fuels and the finite availability of these resources have shifted a greater emphasis on renewable sources of energy.

Another factor of significance is the impact humans are having on the environment. Use of renewable resources will reduce the pollution added to the environment.

2.1. Research Question

The purpose of this research project is to investigate the application of mechatronics to harness renewable energy. With the exponential growth of the population and the continued depletion of carbon-based fossil fuels, alternative power sources must be realized. The advancements in energy storage and system control tools allow renewable energy to be a more viable solution than in the past. Examination of how to harness renewable energy will lead to developments that define the strengths and flaws of utilizing renewable energy as a long term energy source.

The scope of this research project will be focused on the application of Mechtronics in harnessing solar energy. The research question will be “What is the potential energy gain from a real-time intelligent solar tracker?” A prototype solar tracking array fitted with photovoltaic panels will be developed to adjust solar collecting positions dynamically. It is presumed that the energy gained from optimal collection will exceed the energy requirement of continuous monitoring and adjustment.

There are numerous potential variables of this research project such as:

1. Dependent Variable - The amount of voltage collected
2. Independent Variable - The position of the collection array
3. Intervening Variable - The degree change in temperature
4. Intervening Variable - The percent change in humidity
5. Intervening Variable - The amount of hours there is daylight

The following assumptions will be made.

1. A flat solar photovoltaic panel will be placed ten feet from the solar collection array. It is assumed that this will provide a valid head to head comparison for performance gains of the array.
2. Multiple days shall be recorded. It is assumed that that multiple recordings on different days will simulate a population of arrays.
3. Days with possibility of precipitation will not be included. The assumption made is that precipitation will not affect the differential collection capability of

the collection array. The decision of excluding these days is based on concerns of equipment protection. Furthermore it also assumed that any industrial application will have adequate weather protection for sensitive components.

4. Any partial day recordings will be considered valid based on the assumption one: that the presence of flat panel makes it a valid comparison as long as exposure time is equal.

2.2. Scope

This research project is to access the application of mechatronics to enhance the viability of renewable energy as an alternative energy. The scope of this research project will be focused on harnessing solar energy. Solar energy was chosen do to its availability. The industry of photovoltaics has experienced enormous grow in the past decade.

The harnessing of solar photovoltaics energy has many aspects that may be refined. There are electrical circuit inefficiencies in large grid systems, losses from physical positioning, and a lower energy yield. The project scope will be further narrowed to losses from physical positioning.

2.3. Definitions

Definitions for this project are shown in Table 1.1

Table 1.1

Solar Cell	Photovoltaic devices that convert sunlight directly into electricity without moving parts	Nansen, 1995
DC to DC Converter / Switchmode Converter	Allows energy at one potential to be drawn, stored as magnetic energy in an inductor , and then released at a different potential.	Lee, 2009
MPP	Maximum Power Point is located at the knee of the power-voltage curve	Kasa, 2000
Solar Module/Panel	An assembly of solar cells	

2.4. Assumptions

The assumptions of this research project the following:

- There are no requirements for weather conditions during test trial.
- Ten foot spacing is sufficient to prevent the array from substantially shadowing the stationary panel.
- The array is an accurate representation of a population of solar collectors.
- Six trials is an appropriate performance sample.

2.5. Delimitations

The delimitations of this project are:

- Changing weather conditions during trials.
- The effect of humidity on the collection differential.
- The effect of temperature on the collection differential.
- The effect of humidity on the energy storage.
- The effect of temperature on the energy storage.
- Collection differences from testing locations.
- Additional loads added on the system due to wind.

2.6. Limitations

The limitations of this project include:

- The size scale of solar collection array.
- The single sample size of test.
- Time length of trials based on weather.
- Locations available for testing.

3. Literary Review

The research surrounding solar energy has a brief history of rapid growth. Bell Telephone Laboratories originally created Solar Cells during the 1970s (Nansen, 1995). Utilization of this developing technology may lead to long-term solutions to the growing energy crisis.

3.1. New Sources of Energy

With the continued damage to the environment and growth of energy demands new sources of energy must be realized for continued prosperity. Experts can all agree that two basic criteria must be observed to be considered a viable option. Energy must be low cost and reliable (Meisen, 2002; Nanson, 1995). Other criteria to be considered are environmental effects (Meisen, 2002; Nanson, 1995) and usability of the type of energy (Aronson, 2009; Nanson, 1995).

Aronson (2009) said:

“Solar and wind energy, classified as intermittent power, are potential sources of tremendous energy. But, the long-standing challenge is converting that energy into usable power. (p. 48)”

3.2. An Industry in Growth

Continued experimentation has driven the growth of this technology to levels of practical application. The advances in manufacturing and growing market demand has lowered the cost of solar cells to one-seventh of the production cost during 1980 (Wolcott, 2002). Nansen said, “worldwide output of solar cells has increased fifty-fold since 1978 (p. 92).” Meisen said, ”IIASA/UNDP have offered a radically different scenario that shows renewable energy, especially solar, becoming a major market share by 2050 (p. 117).” Aronson has identified the following “categories of solar power systems.”

- Multimegawatt systems supplying large facilities or towns.
- Commercial systems that supplement grid power or are the only power source for a single building.
- Single residential systems to power a single home or farm.

Solar power units are now produced in three general configurations: Flat-plate PV, Concentrator Design, and Non-photocell version of the concentrator (Aronson, 2009).

3.3. Growing Concern for the Environment

As our current utility systems are based on the burning of carbon fuels environmentalists are studying the effects on the environment. Energy utilities produce greenhouse gasses. As energy demand rises, the production of greenhouse gasses will also rise. Nuclear power is another alternative that is harmful to the environment.

Nansen (1995) said:

“Nuclear power uses a depletable resource and also leaves in its wake toxic nuclear waste.” “Hydroelectric power is generated by a wonderful renewable source, but there are few rivers left in the world to dam and there is a growing concern over the impact dams have on the fish population (p. 7).”

From Nansen’s statement we see the implications of hydroelectric power and how its effects the ecosystem in rivers. Rose and Pinkerton emphasize the pollution caused by coal and nuclear power.

Rose and Pinkerton (1981):

“Solar cells have no known adverse environmental impacts during operation. While coal power produces sulfur and acid rain, nitrogen oxides, coal dust, and carbon dioxide, and nuclear power produce wastes that are dangerous for thousands of years and can be used to make nuclear bombs, solar cells have none of these hazards (p. 148-149).”

A small amount of waste is created during the manufacturing process of solar cells. The low one time environmental impact of solar cells is significantly less than that of other power sources.

3.4. How Photovoltaics Work

A photovoltaic cell is a single piece-nonmoving panel that generates electric current when exposed to sunlight.

Nansen (1995) stated:

“When the cell is exposed to sunlight the light dislodges electrons form the atoms in the cell material. As the negatively charged electrons flow to one side of the cell, the other side gains a positive charge from the deficiency, creating an electrical charge between connectors (p.92).”

3.5. Applications of Machine Intelligence to Solar Energy

Solar Collection yields a low amount of electrical energy. Studies have shown that on large systems uneven collection can cause some solar cells to act as resistive loads on the system. This can significantly impact the system’s output. There have been several applications of machine intelligence to improve system efficiency. This is commonly referred to as maximum power point tracking (MPPT).

In the study by Roman, Alonso, Elorduizapatarietxe, Ibanez, and Goitia (2006) a PV array with 20 PV modules were wired in series for a residential rooftop application. Roman, et al., (2006) continue stating, “Unfortunately, avoidance of partial shading in this environment is not always feasible. Trees, buildings, television aerials, and other roof structures result in a substantial reduction in system performance (p. 1067).” For this study, five of the 20 PV modules were installed in the shadow of a chimney (Roman & et al., 2006). Roman, et al., (2006) explain that when connected in series PV modules are forces to draw the same current. Roman, et al., said,”The shaded modules would act as passive loads.” The system proposed utilized machine intelligence to determine which modules had low power output and disconnected them from the system. This increased the efficiency of the system.

Issam Houssamo, Fabrice Locment, and Manuela Sechilariu (2010) compared to algorithms for maximum power point tracking. The observe and perturb commonly found in literature and industry utilizing a voltage difference was compared to incremental conductance algorithm, which utilizes the derivative of the photovoltaic system impedance (Houssamo et al., 2010). Two identical photovoltaic systems were set up consisting of eight solar panels each programmed to perform one of the two algorithms. The feedback data was the load impedance of the photovoltaic system. The systems made adjustments through the use of four DC-DC converters (Houssamo et al., 2010). Houssamo and others state, “It is found that the P&O method, when properly optimized, can have mostly the same MPPT efficiencies as INC method and is highly competitive against other MPPT algorithms by its easy implementation" (p. 2387).

Another study was conducted by Jalili-Kharaajoo. Jalili-Kharaajoo (2004) studied the effects of a neuro-fuzzy controller to adjust the flow rate or oil. This oil was heated for a solar thermal power plant. Jalili-Kharaajoo (2004) explains, "Thermal energy storage in the tank can subsequently used to produce electrical energy in a conventional steam turbine/generator or in a solar desalination plant operation."

In 2008, Mohammed S. Al-Soud, Essam Abdallah, Ali Akayleh, Salah Abdallah, and Eyad S. Hrayshat developed a parabolic solar cooker that automatically tracked the sun. The cooker consisted of a parabolic array of mirrors focusing on a black steel tube in the center. Two motors controlled the tilt and rotation of the cooker. Water was pumped into the black steel tube on one end and exited the other end. A PLC controlled the system and adjusted the cooker based on previously calculated solar angles. Incremental position adjustments were made in 10-20 minute increments on the horizontal axis and 15-35 minute increments on the vertical axis (Al-Soud, et al., 2010). The parabolic solar cooker heated the tube water to temperatures of 90℃ in Amman, Jordan (Al-Soud, et al., 2010).

3.6. Machine Intelligence Applied to Solar Tracking

The simplest and most efficient technique to maximize the collection potential of a solar cell is to have line of sight orientation with the sun. This maximizes the exposure potential of the collection surface. Lee, Chiang, Chou, and Lin (2009) said, “It is necessary to track the sun to a high degree of accuracy.” When the PV system is oriented at a right angle the optimal energy collection can be realized (Sungur, 2008)

A study conducted by Lee and others (2009) focused on the potential energy gain by various closed-loop and open-loop control algorithms. These various tracking methods were compared to a non-tracking system. Lee and others (2009) concluded, “Compared to their traditional fixed-position counterparts, solar systems which track the changes in the sun’s trajectory over the course of a day collect far greater amount of solar energy, and therefore generate significantly higher output power (p. 3887).”

Xinhong, Zongxain, and Zhengda (2007) studied the applications of a FPGA development board to intelligent solar tracking. Utilizing the Nios II Embedded Processor, Xinhong and others developed a solar tracking system. The experiment was tested by comparing collection capacity of the unit when it was stationary to when it was dynamic. The results of the experiment yielded 59,904 J more than the array as a stationary unit (Xinhong, et al., 2007). Xinhong, et al., claim, “This system can achieve the maximum illumination and energy concentration and cut the cost of electricity by requiring fewer solar panels, therefore, it has great significance for research and development (p. 217)."

Cemil Sungur (2008) studied the application of a PLC to intelligent solar tracking. His prototype used photo sensors and an algorithm applying solar angles to solar tracking. Sungur said , "In these photo sensor systems used, unstable states may exist under overcast and partly cloudy weather conditions when the photo sensors do not see the sun (p. 1120)."

In 2008 W. Stephen Woodward analyzed the maximum power point tracking control algorithm perturb and observe. He states, "The perturb-and-observe algorithm is the basis of the maximum power point tracking control circuit but with a twist which achieves a feedback function equivalent to a current times voltage power calculation but without the complexity of a conventional multiplier (p. 51)." The two conditions required for this relationship are the logarithmic behavior of transistor junctions and the mathematics of adding logarithms (Woodward, 2008).

Ibrahim Sefa, Mehmet Demirtas, and Ilhami Colak (2009) designed a single axis sun tracking system in Turkey. The sun tracking system developed by Sefa and others included a serial communication interface based on Rs 485 to monitor whole processes on a computer and record the data. Feedback data was recorded by two photoresistors. The solar cell was aligned at a fixed 41° facing south (Sefa, et al., 2009). A microcontroller observed and controlled the east-west rotation of the tracker by means of 24V 50W dc motor (Sefa, et al., 2009).

The results of the measured energy showed an increase up to 46.46% of collected solar energy (Sefa, et al., 2009).

Yusuf Oner, Engin Cetin, Harun Kemal Ozturk, and Ahmet Yilanci (2009) developed a solar tracker utilizing the application of a spherical motor. The motor contains a rotor containing a four pole magnet surrounded by eight individually energized stator poles (Oner, et al., 2009). With the magnet in the middle direction is controlled by the surrounding stator poles (Oner, et al., 2009). This design allows for three degrees of freedom. The degrees of freedom being forward and back tilt, a left and right lateral tilt, and rotation along a z-axis. Feedback data is recorded by two phototransistors in the middle of the top and left side of the solar panel. The feedback data is fed into a PIC 16F877 micro-controller for directional adjustments (Oner, et al., 2009). The control logic of the micro-controller adjusted the solar panel in increments in 5° (Oner, et al., 2009). By utilizing a spherical motor allows for one motor to perform the same function gained by two conventional motors.

An article by Al Presher reported recent developments in the applications of solar tracking. Reliathon, a Suntech Power Holding, developed a solar tracking system, Duratrack for utility scale solar plants in 2010 (Presher, 2010). Al Presher reported, “What makes the DuraTrack solar tracker unique from other companies in horizontal axis tracking for the utility market is the drive system. Other horizontal tracking systems use a push/pull linkage to move many rows with one linear actuator or motorized drive, while Array Technologies' design uses a rotating drive linkage” (p. 39). The flexible drive allows for installation of the Duratrack system over various terrains with ease (Presher, 2010). The drive line rotates the panels form east to west. The system is controlled by a PLC utilizing sensory data form GPS inputs (Presher, 2010). The Duratrack system comes in two models, one 0 degree tile and one 20 degree tilt. Presher quotes Brian MacCleery, a senior product manager at National Instruments who focuses on green and renewable energy projects stating, “One of the drivers in solar tracking is the emergence of concentrated photovoltaics. Because the optics used in these systems magnify and concentrate the sunlight onto a small solar cell, they require very precise two-axis tracking of the sun to achieve peak output” (p. 40). MacCleery continues citing research conducted at the Applied Research Center for Intelligent Control and Automation. MacCleery states the research being done utilizes Labview in combination with SolidWorks to create virtual prototypes of sun tracking systems (Presher, 2010)..

In 2010 another solar tracking system was designed by Nader Barsoum and Pandian Vasant of Curtin University in Sarawak, Malaysia. Barsoum and Vasant’s prototype utilized a control circuit based on a PIC16F84A microcontroller (2010). The prototype utilized feedback data collected from four cadmium sulfide photoresistors (2010). The cadmium sulfide photoresistors were selected based on darkness and light saturation resistance (2010). A perpendicular obstruction was placed between any given pair of photoresistors. The purpose was to increase the voltage difference between any given pairs not perpendicularly aligned. The tracker aligning was performed by two 12 volt motors. The motors drove the alignment utilizing a chain gear system to produce the necessary torque. Barsoum and Vasant concluded, “A lot of time was needed to be set aside for verification and testing due to the unpredictability of weather and debugging issues (p. 158).”

Ghosh, Bhowmik, and Hussain studied how the orientation and tilt angle of a solar cell affected performance of a solar radiation conversion system. Ghosh and others utilized three mathematical models- the Isotropic, the Klucher and the Perez model to determine hourly and seasonal optimum tilt angles. The Isotropic model is a simplified model. In the Klucher model the cloud conditions are adjusted for (Ghosh, et al., 2010). The Perez model is designed to compensate for a variety of weather conditions (Ghosh, et al., 2010). The three models were evaluated for accuracy by having their root mean square, bias error, and mean relative percentage error (Ghosh, et al., 2010). The anisotropic Perez model resulted in the smallest root mean square reading 0.09 for monthly tilt factor (Ghosh, et al., 2010). Ghosh and others state, “The results demonstrated that a gain in the amount of solar radiation received by the surface mounted tilt angle at monthly tilt angle lied in the range of 0%–55% (p. 1296).”

4. Study Design Methodology

This research project is to access the application of Mechtronics to enhance the viability of solar energy as an alternative energy source. The type of research done in this project will be quantitative. Equipment for this experiment include two solar panels of equal size and output ratings, three equal sets of nickel metal hydride cells, and a real-time prototype solar tracking array. Each solar panel will feed directly into to a set of nickel metal hydride cells. The third set of nickel metal hydride cells will power the solar tracking unit. The location for the trials will be top level of the Grant Street Parking Garage at Purdue University. For each trial the stationary solar panel will collect energy within 10 feet of the solar tracking unit for a period of 8 hours. Voltage was verified every 30 minutes. As the C-Rio battery depleted it was swapped with the charging battery. Voltage of both the C-Rio battery and the charge battery was recorded during these exchanges. The study will include six trials consisting of three solar tracking trials (Shown in figure 4.1) and three stationary trials (shown in Figure 4.2). Trials were stopped due to inclimate weather shall be recorded with their exposure time. Descriptive statistics will be performed on the data. This will develop an overall differential in collection tendencies.

Figure 4.1. Solar Tracker collection trial 2 on 3/2/11.

Figure 4.2. Solar Tracker collection trial 5 on 3/18/11.

4.1. Prototype Proposal

The researcher will fabricate the proposed real-time solar tracking array. The various parts required for the array are framing, a National Instruments Compact Rio programming module, three optical sensors, one dc motor, one stepper motor, and three sets of nickel metal hydride cells. The Compact Rio module will utilize three input/output modules. One National Instruments Model 9201 8-Ch ±20 mA, 200 kS/s, 16-Bit Analog Current Input Module will be used to receive sensory data from the three photoresistors. Two National Instruments Model 9505 Brushed DC Servo Drive Modules will be used to drive the 12 Volt motors. The tracking array will be able to pivot on a tilting axis by way of a 12 volt DC motor with attached gear box. The tracking array rotation will be performed by the 12 volt DC motor. The National Instruments Compact Rio model 9012 programming module will be programmed in Labview 8.5.

4.2. CAD Model

To determine the approximate materials required to develop the framing for the prototype a virtual model was developed in AutoCAD. There were several constrained dimensions in the development of the model. The first constraint was the height, width, and thickness of the solar panel. The second was the height, width, and thickness of the Compact Rio controller. Additional design considerations were given to the height of available casters to provide support for the base. The final CAD Model is shown in figure 4.3.

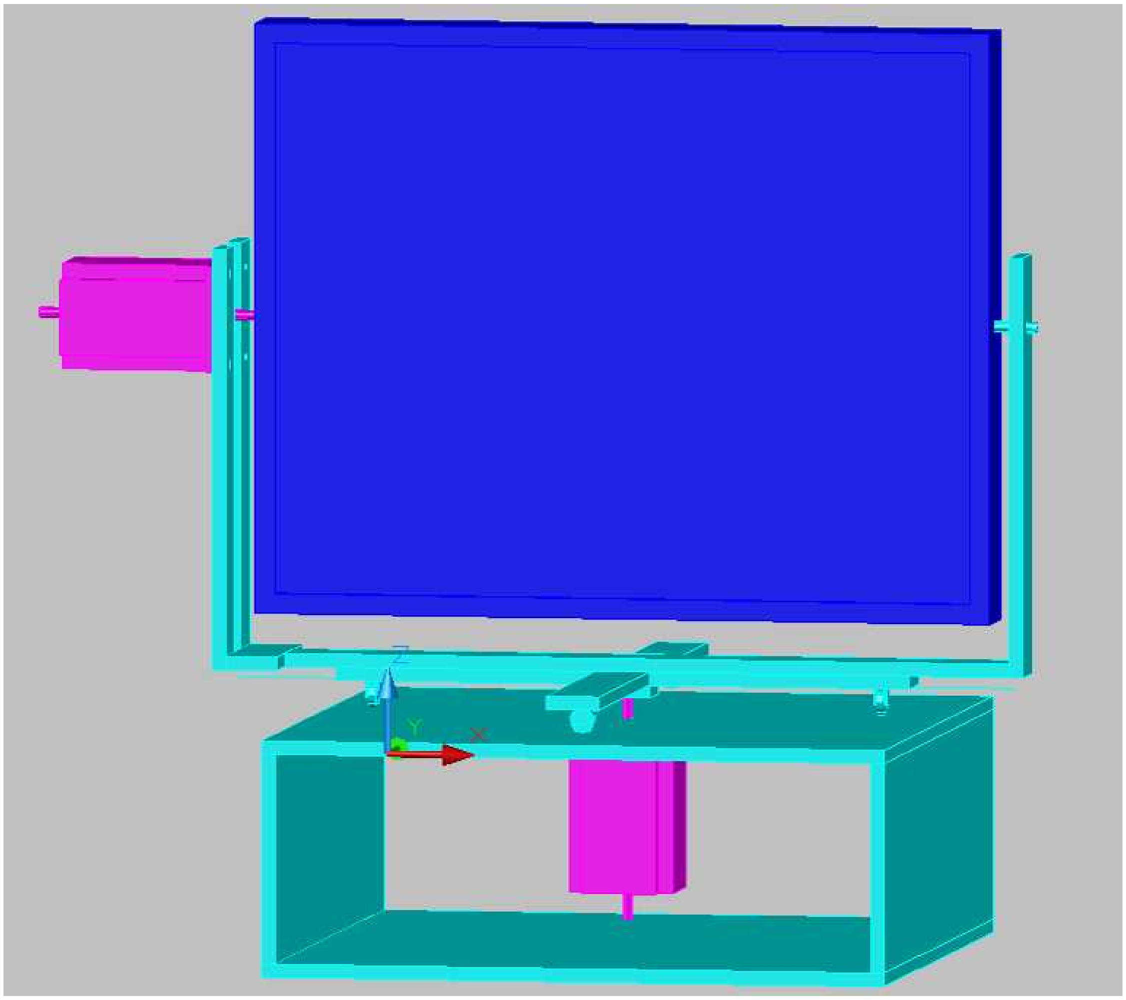


Figure 4.3. AutoCAD Model of prototype.

4.3. Prototype Fabrication

Materials used for construction include three 16” x 20” x $^3/_8$” polyurethane cutting boards. The edges were removed as ½” bars. Another 1½” was cut lengthwise on two of the boards to serve as the structural beams. These two cutting boards were cut again widthwise 4” from the handle end. The newly cut rectangle boards are then combined to form the base and walls of the prototype. One of the 1½” x 20” bars is cut a length of 10”. A 1” hole is drilled on one side creating space for a rollerblade bearing. The Reminder of the bar is attached to the complete 1½” x 20” bar. The Remaining cutting board is cut to an 11” square. It then had the corners removed as 4” squares leaving the remaining in a cross shape. This becomes the wheelbase of the array. $1^3/_4$” casters are placed at the ends of the cross and it is attached to the main beam. Using two “L” brackets the bar with the bearing is mounted upright on the end of the main bar. Then one of the ½” edge bars was cut to 2” and mounted 3” from the edge of the free end of the main bar using two “L” brackets. Two other ½” edge bars are mounted vertically to the new brace providing 2 bars for motor mounting. The completed prototype is shown in figure 4.4.

Figure 4.4 Completed Solar Tracker Prototype

4.4. Feedback Design

The Feedback Design will utilize cadmium sulfide photoresistors as the optical sensors. The cadmium sulfide photoresistors were selected for their simplicity and availability. A bag of photoresistors from RadioShack contains five photoresistors of various sizes seen in figure 4.5. The photoresistors were numbered; 1,2,6,7 being large photoresistors, 3,4,8,9 being medium size, and 5,10 being small resistors. A test circuit as seen in figure 4.6, was built testing each photoresistor at one, two, three, four, and five volts. These test compared the photoresistor reaction to light saturation and voltage change. Performance curves in appendix page 45 showed that sensors 3, 7, and 8 were the most similar operating between one and two volts. A 1.5 volt AA battery supplies the input voltage for the final circuit in figure 4.6, The photoresistors are to be aligned on the top left and right and to the bottom of the solar cell. Attached to the back side of the solar cell the photoresistors are shimmed to half the height of the thickness of the solar cell. This is to create a larger differential between the voltage of top and bottom. It was assumed that the distance between the left and right photoresistors would already have a large enough voltage difference. The top right sensor input voltage is wired to AI0 while its output voltage is wired to AI1 shown if figure 4.7. The top left sensor input voltage is wired to AI2 while its output voltage is wired to AI3 shown if figure 4.7. The bottom sensor input voltage is wired to AI4 while its output voltage is wired to AI5 shown if figure 4.7.

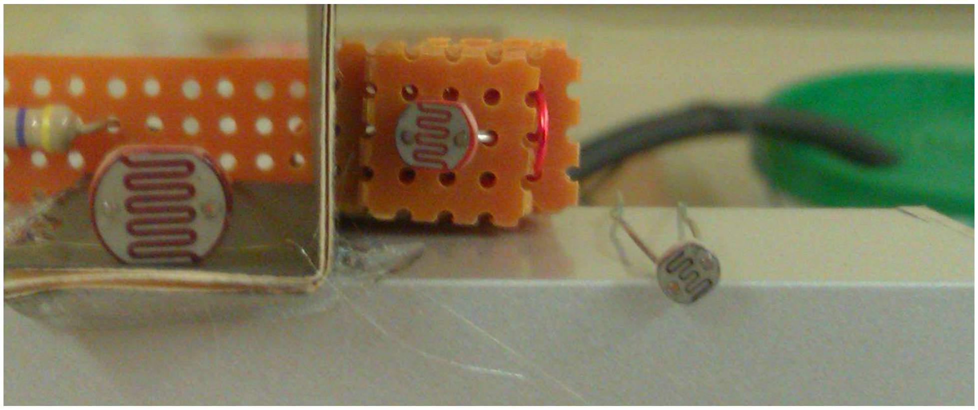
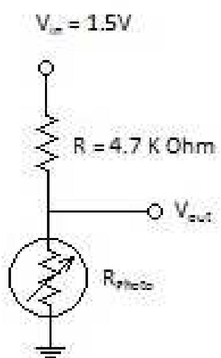


Figure 4.5. Three Sizes of photoresistors are found in RadioShack photoresistor bag. Two large, two medium, and one small are in each set.



$$\frac{R_{photo} \times V_{in}}{R_{photo} + R} = V_{out}$$

Figure 4.6. Test Circuit for Photoresistors to control module. When the photo resister is exposed to light V_{out} will decrease.

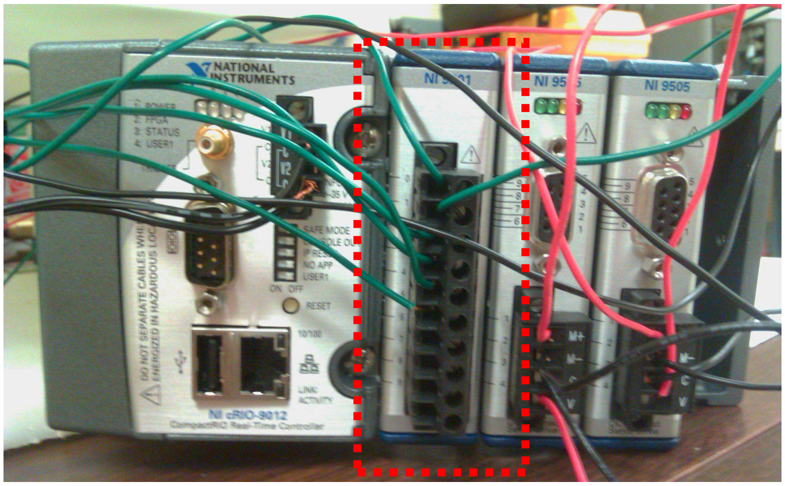


Figure 4.7 Compact Rio with analog input module hilighted

4.5. Programming

The strength of utilizing the Compact Rio controller is its interface with Labview. Labview developed by National Instruments in 1986 is short for Laboratory Virtual Instrumentation Engineering Workbench. Labview is unique due to its graphical interface. Programming in Labview utilizes three components: the front panel, the block diagram, and the controls palette. The front panel is typically used to display data or provide user controlled inputs. The block diagram has been developed in a flow chart like form for ease of use. It is used to define the inputs and outputs through a series of nodes. The controls palette is the library of command functions available for use in Labview.

There are several benefits of Labview's graphical approach. The graphical interface allows novice programmers to write programs by dragging and dropping graphical icons of commands and tools that they find familiar. Another benefit is the ease of documentation of the program details. The graphical interface also provides a benefit in editing allowing chucks of a program to be copied or removed at will. Lastly Labview's graphical interface provides visual assistance in debugging. When a program is incomplete the run execution button is displayed as a broken arrow and selecting it will move the user to the area of the block diagram with the error selected. In addition when connections are made with incompatible data types Labview marks the connection with an "X".

The control program was a closed programming loop based on feedback principles. The three cadmium sulfide photoresistors will be the inputs. The Labview sequence for these sensors reading is shown in figure 4.8. The Compact Rio is programmed so it can obtain the resistance data from the photoresistors and turn left or right, tilt forward or backward. The Labview sequence for the motors performing the rotation or tilt is shown in figure 4.9. In figure 4.10 the sequence shown processes the data from figure 4.8, calculates a voltage differential between the sensor readings, and activates the appropriate figure 4.9 motor. The Compact Rio processing power is far greater than required for this task. Realizing the performance may be too fast a delay timer is needed. Barsoum and Vasant state, "the drawbacks associated with high frequency clock are: their requirement for large power consumption and also possibly the electromagnetic interference (p. 155)."

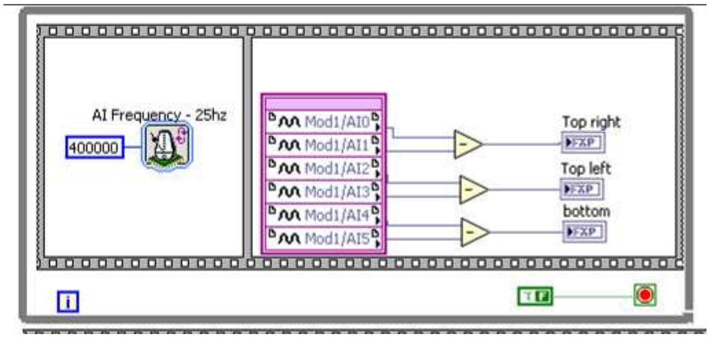


Figure 4.8. This loop takes voltage readings with the sampling frequency 25 Hz. These readings are recieved from the photoresistor circuits and the difference is calulated. This difference is then defined as fixed point data type.

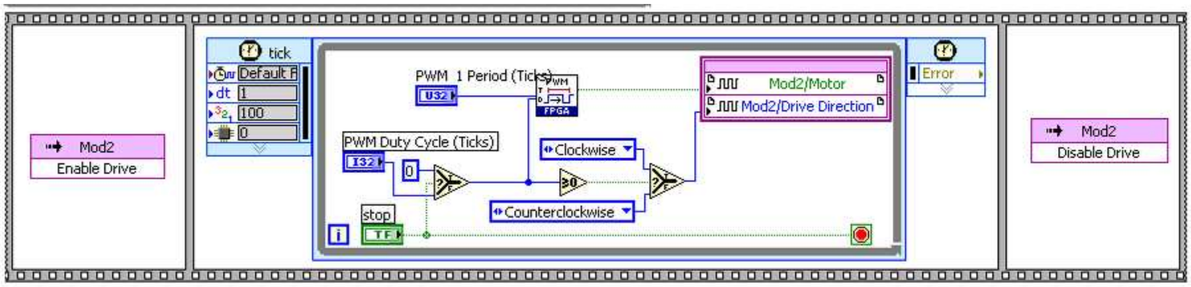


Figure 4.9. This sequence enables the motor drive module. The pulse width modulation period and duty cycle are defined here. The control signals sent from the control to FPGA are pulse width modulation duty cycle ticks, which could be positive, zero and negative numbers. Since the sun tracker should be working in a slow mode, the differential amount is not used in the program to determine the duty cycle ticks of the PWM wave. This means the duty cycle ticks of the PWM wave is constant in this program and the differential amount only decides the moving clockwise or couter clockwise direction and the time that costs to arrive at the desired status. Two of these sequences are needed, one for each motor module.

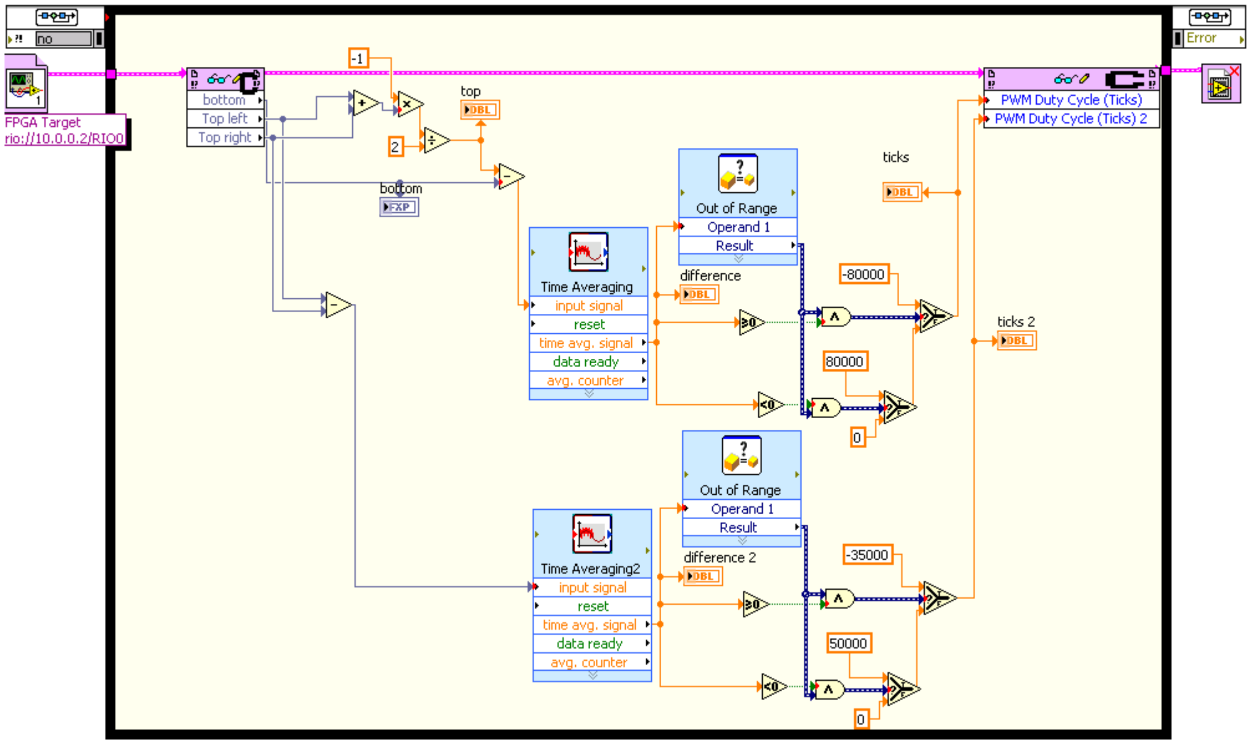


Figure 4.10. This is the project file for the solar tracker prototype. The program recalls the previously defined sensor data for positioning calculations. The top sensors are averaged to create an overall top difference difference. A top bottom difference is calculated compating this overall top to the bottom. That difference is then averaged across 100 samples. A duty cycle is fed back in the motor drive 1 loop based on a positive or negative difference in sensor average. The left and right sensor difference is determined. That difference is then averaged across 100 samples. A duty cycle is fed back in the motor drive 2 loop based on a positive or negative difference in sensor average.

4.6. Measurement Units

The primary unit of interest is volts collected. This was measured by using an Ideal 61-766 volt meter to check the voltage of the nickel metal hydride cells. Other units of measure are weather conditions and hi and low temperatures gathered from weather.com.

5. Results and Analysis

Solar collection data was taken for seven days. On the first day of energy collection it was discovered that the solar tracker was unable to determine a distinction in left right sensor readings. In an attempt to increase this distinction, the dead zone in the program was reduced allowing the most minor differences to activate motor direction. The result was unsuccessful causing a continuous clockwise rotation and a seesaw motion by the tilt motor. During the second day of energy collection the dead zone in the program was made slightly larger. This allowed a difference in tilt readings; however the difference in left right readings was completely in the program's dead zone. This data as unintended provided useful insight as to the tendencies of the solar tracking system. From the voltage data in table 5.1, it is seen that the voltage drained by the non-operating motor (M2 Batt) was significantly close to that of the utilized tilt motor (M1 Batt). These findings suggest that as built the solar tracking system would not experience significant power savings using periodic data. Trial two was ended early to develop a way to incorporate rotation into the motion. Before the third day of energy collection shades were added to the solar tracker. This allowed the left right readings to have a differential and allowed rotation as well as tilt. Energy collection days five to seven serve as a control of the stationary collector. Trials five and six were ended prematurely due to rain.

The results have shown that a 28% increase in voltage collected with solar tracking. The control trials of stationary collection had a larger net voltage gain seen in tables 5.1 and 5.2. This is partially due to power requirements of C-Rio controller and motors. This difference is also partially due to the low collection potential of the small solar panel. Boxwell's solar irradiance calculator calculates solar irradiance for Lafayette, IN in March averages 3.48 kwh/m^2/day seen in appendix page 50. This figure simplifies to 145 wh/m^2. Converted to in^2 is .094 wh/in^2. The 15 in by 12 in solar panel is therefore exposed to 16.83wh. Since the active tracking collects 3.85 wh only 23% of the solar irradiance is collected.

Date	3/1/2011	3/2/2011	3/11/2011	3/17/2011	3/18/2011	3/22/2011	3/24/2011
C-Rio Batt	0.4	5.4	7.9	8	0	0	0
M1 Batt	0.3	0.5	0.9	0.9	0	0	0
M2 Batt	0.3	0.4	0.9	0.9	0	0	0
Charge	-1.6	-8.4	-12.5	-12.6	-7.8	-8.4	-9.9
Net	-0.6	-2.1	-2.8	-2.8	-7.8	-8.4	-9.9
Hours	1	4	8	8	5	7	8

Table 5.1. This table displays recorded energy collection and duration of collection period in volts.

Date	3/1/2011	3/2/2011	3/11/2011	3/17/2011	3/18/2011	3/22/2011	3/24/2011
C-Rio Batt	0.4	1.35	0.9875	1	0	0	0
M1 Batt	0.3	0.125	0.1125	0.1125	0	0	0
M2 Batt	0.3	0.1	0.1125	0.1125	0	0	0
Charge	-1.6	-2.1	-1.5625	-1.575	-1.56	-1.2	-1.2375
Net	-0.6	-0.525	-0.35	-0.35	-1.56	-1.2	-1.2375
Weather	Sunny	Pt cld	Pt cld	Pt cld	Pt cld/Rn	Pt cld	Cld/Pt cld
Temp Hi	47	44	48	73	59	66	38
Temp Lo	20	30	30	46	37	47	23

Table 5.2. This table displays in volts average energy usage per hour, negative values are energy gains.

5.1. Commercial Applications

The current design of this solar tracker as built is not currently commercially viable as a production product. This is due to the low cost of electricity combined with the low amount of potential energy collected. Figure 5.1 shows the present worth value of the solar tracking system based on trial three's net hourly collection, the electrical rate of \$0.10 per kilowatt hour, the base cost of National Instruments C-Rio at \$1200, and development cost of the tracking prototype at \$400 at an interest rate of 5% for a 10 year period. From the calculations in figure at 5% interest and averaging .77 watts an hour the tracker will not pay itself off in 10 years. This is due to the principle investment of the compact Rio costing \$1200. In addition with an average collection of .77 watts causes inflation to negate any savings form energy collection. The economic analysis performed in figure 5.2 shows that the photovoltaic panel would need to collect 710 watts an hour to pay itself off in 10 years.

$V_{gain} := .35 \qquad A_{gain} := 2.2$

$P_{gain} := V_{gain} \cdot A_{gain}$

$P_{gain} = 0.77$

$P_{tracker} := 400 \qquad R_{ele} := .1 \qquad PofA_5 := 7.72 \qquad P_{crio} := 1200$

at 10 years

$$PW := -P_{tracker} + -P_{crio} + \left(365 \cdot 8 P_{gain} \cdot \frac{R_{ele}}{1000}\right) \cdot PofA_5$$

$PW = -1598.2642$

Figure 5.1

$P_{gain} := 710$

$P_{tracker} := 400$ $R_{ele} := .1$ $PofA_5 := 7.72$ at 10 years $P_{crio} := 1200$

$$PW := -P_{tracker} + -P_{crio} + \left(365 \cdot 8P_{gain} \cdot \frac{R_{ele}}{1000}\right) \cdot PofA_5$$

$PW = 0.5104$

Figure 5.2 Required energy collection to 10 year payback at 5% interest

6. Conclusion and Recommendations

The purpose of this application was to design and implement a two-axis solar tracking system utilizing the National Instruments C-Rio. In addition this approach utilizes a 3 photoresistor system.

6.1. Design Challenges

There were several challenges during the development and testing of the solar tracker. Originally it was conceived that a smaller 3 volt motor would be able to drive the solar tracker with the assistance of a planetary gear system. This initial notion failed however due a combination of the slip allowance in the plastic planet gear set and the weight of the upper tracker assembly. The result of these issues caused the motor to grind the plastic gears instead of rotating the array. This motor was replaced with one of the two 12 volt high torque motors.

Another design issue was created by this replacement. The motor replacement created a height differential requiring an additional shaft to be added to the upper array and coupler to join it to the motor. Due to human inaccuracy with hand tools the added shaft was not exactly straight. Though the upper array could rotate the motion was jerky. This due to the support wheels getting stuck between the tilted shaft and the base the support wheels rest on. This problem was rectified with the utilization of a flexible coupling (shown in figure 6.1) allowing this stress to be distributed.

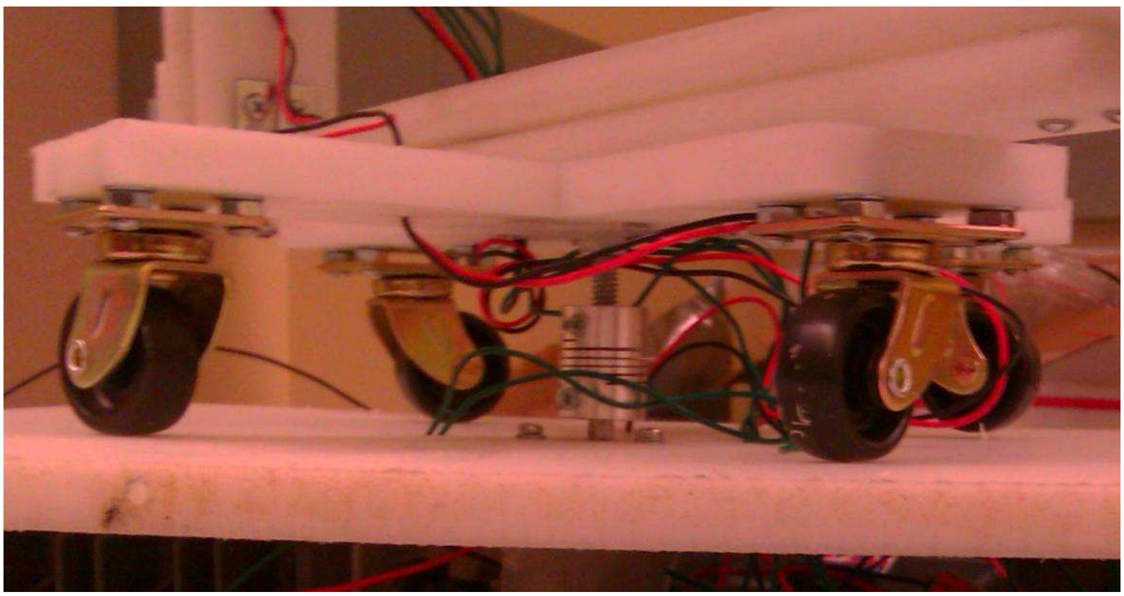


Figure 6.1 Flexible Coupling

The solar tracker was originally was initially tested in a lab setting in a dark room. During the energy collection trials the tracker motion was erratic, possibly due to fluxuations in the voltage readings. The solar tracker sensitivity needed to be decreased to minimize this motion. This solution created a difficulty in distinguishing left and right readings. A final solution was to add vertical shades (Shown in figure 6.2) to the solar tracker. With these shades, sun position would create a shadow over the photoresistor allowing a significant reading differential to be created.

Figure 6.2

6.2. Lessons Learned

During the testing it was discovered that concrete tends to have a high light reflectance. This caused difficulties in readings. During occasional voltage spikes in photo resistance the solar tracker would tilt downward. When the solar tracker faced downward concrete's reflectance is enough to cause the tracker to continue to tilt to an angle below its natural horizon. A testing area with a lower reflectance would be recommended for any continued studies. Though the solar tracker tracks the sun it does not create an exact perpendicular face to the sun. This is another topic to be further explored. This application utilized cadmium sulfide photoresistors which though simple to set up were extremely sensitive to change. A search for a replacement would also be recommended. Another topic to be explored is to have the differential reading feedback into the duty cycle ticks for pulse width modulation.

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8. Appendices

Solar Collection Data

Date	3/1/2011	Hrs	V/Hr	V/Day	Initial	Final	Difference
C-Rio Batt	0.4	1	0.4	3.2	13.4	13	0.4
M1 Batt	0.3	1	0.3	2.4	26.6	26.3	0.3
M2 Batt	0.3	1	0.3	2.4	26.6	26.3	0.3
Charge	-1.6	1	-1.6	-12.8	12.2	13.8	-1.6

Date	3/2/2011	Hrs	V/Hr	V/Day	Initial	Final	Difference	Initial	Final	Difference
C-Rio Batt	5.4	4	1.35	10.8	13.5	8.9	4.6	13.7	12.9	0.8
M1 Batt	0.5	4	0.125	1	27.1	26.6	0.5			
M2 Batt	0.4	4	0.1	0.8	27.1	26.7	0.4			
Charge	-8.4	4	-2.1	-16.8	10.7	14	-3.3	8.5	13.6	-5.1

Date	3/11/2011	Hrs	V/Hr	V/Day	Initial	Final	Difference	Initial	Final	Difference	Initial	Final	Difference
C-Rio Batt	7.9	8	0.9875	7.9	12.9	8	4.9	14.3	12.5	1.8	14.7	13.5	1.2
M1 Batt	0.9	8	0.1125	0.9	27	26.1	0.9						
M2 Batt	0.9	8	0.1125	0.9	26.9	26	0.9						
Charge	-12.5	8	-1.5625	-12.5	9.6	14.3	-4.7	8	14.7	-6.7	12.5	13.6	-1.1

Date	3/17/2011	Hrs	V/Hr	V/Day	Initial	Final	Difference	Initial	Final	Difference	Initial	Final	Difference
C-Rio Batt	8	8	1	8	12.7	8.1	4.6	14	11	3	14	13.6	0.4
M1 Batt	0.9	8	0.1125	0.9	27	26.1	0.9						
M2 Batt	0.9	8	0.1125	0.9	27	26.1	0.9						
Charge	-12.6	8	-1.575	-12.6	9	14	-5	8.1	14	-5.9	11	12.7	-1.7

Date	3/18/2011	Hrs	V/Hr	V/Day	Initial	Final	Difference	Initial	Final	Difference
C-Rio Batt	0	5	0	0	0	0	0	0	0	0
M1 Batt	0	5	0	0	0	0	0			
M2 Batt	0	5	0	0	0	0	0			
Charge	-7.8	5	-1.56	-12.48	11	13.5	-2.5	8.3	13.6	-5.3

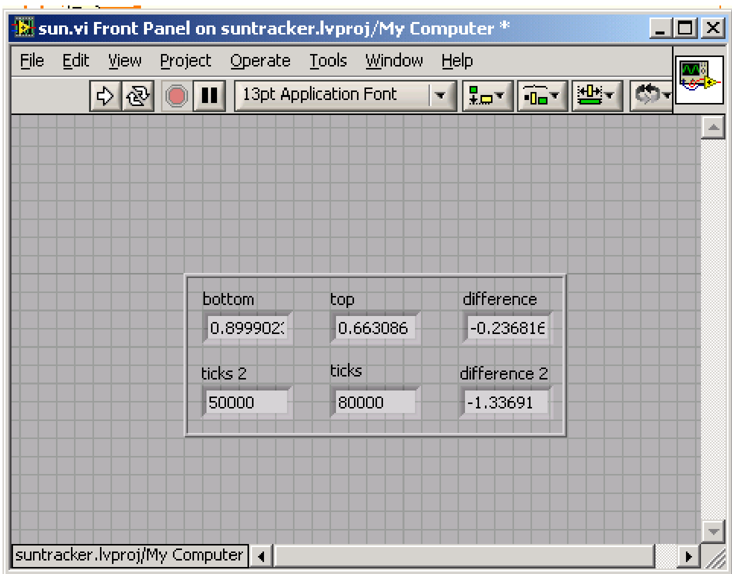
Date	3/22/2011	Hrs	V/Hr	V/Day	Initial	Final	Difference	Initial	Final	Difference
C-Rio Batt	0	7	0	0	0	0	0	0	0	0
M1 Batt	0	7	0	0	0	0	0			
M2 Batt	0	7	0	0	0	0	0			
Charge	-8.4	7	-1.2	-9.6	7.7	13.8	-6.1	11.1	13.4	-2.3

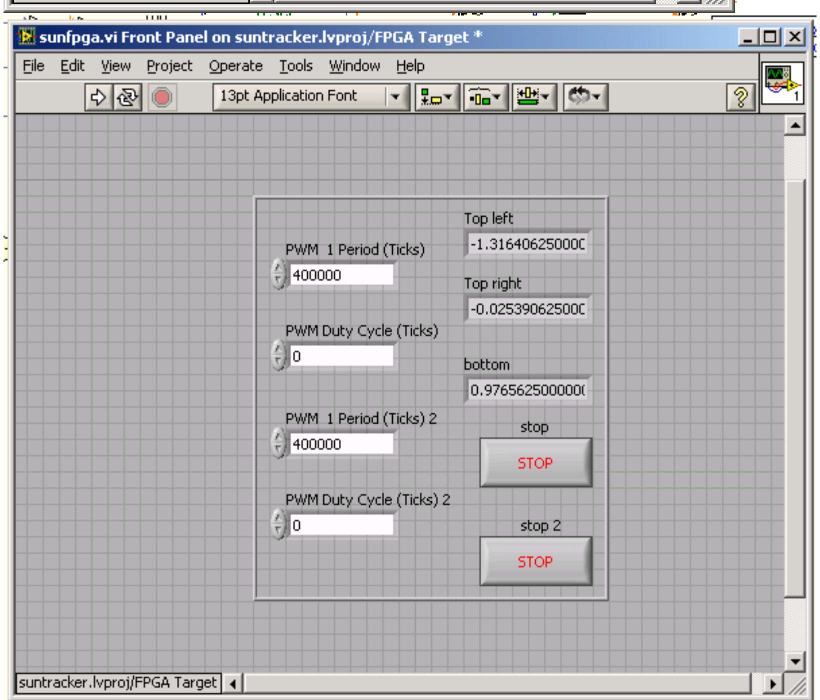
Date	3/24/2011	Hrs	V/Hr	V/Day	Initial	Final	Difference	Initial	Final	Difference
C-Rio Batt	0	8	0	0	0	0	0	0	0	0
M1 Batt	0	8	0	0	0	0	0			
M2 Batt	0	8	0	0	0	0	0			
Charge	-9.9	8	-1.2375	-9.9	7.5	13.8	-6.3	10.2	13.8	-3.6

Weather Data

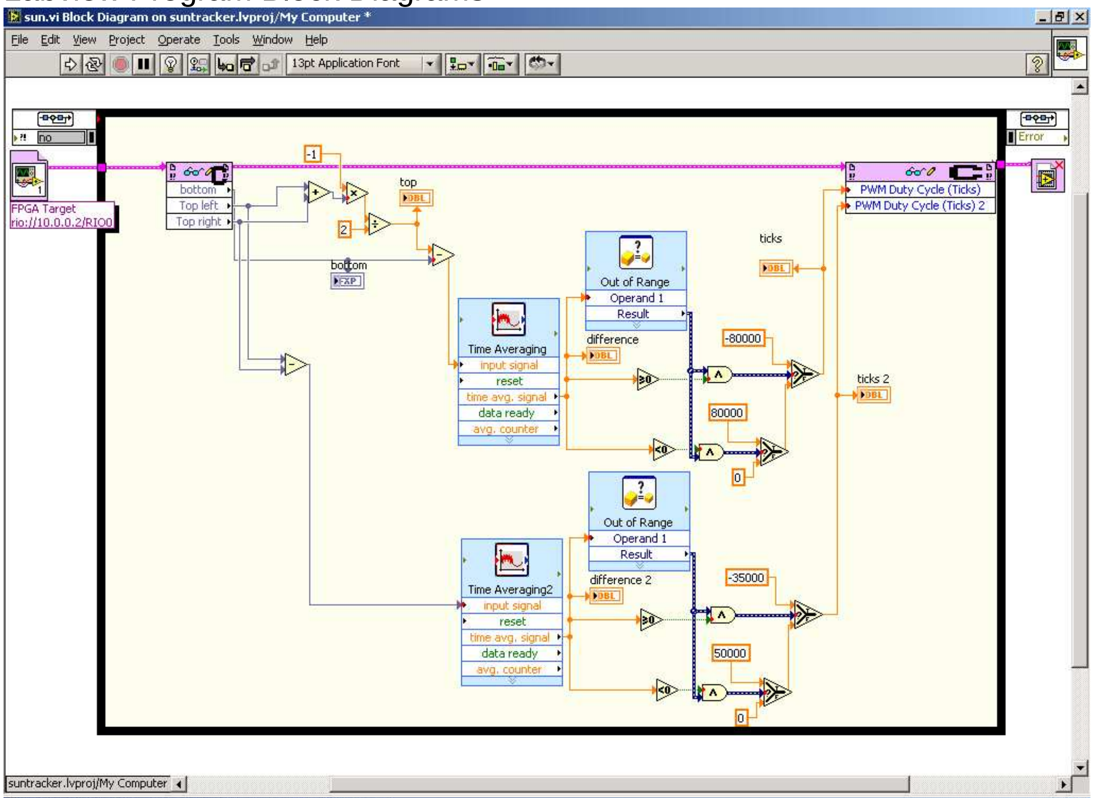
Weather	Sunny	Pt cld	Pt cld	Pt cld	Pt cld/Rn	Pt cld	Cld/Pt cld
Temp Hi	47	44	48	73	59	66	38
Temp Lo	20	30	30	46	37	47	23

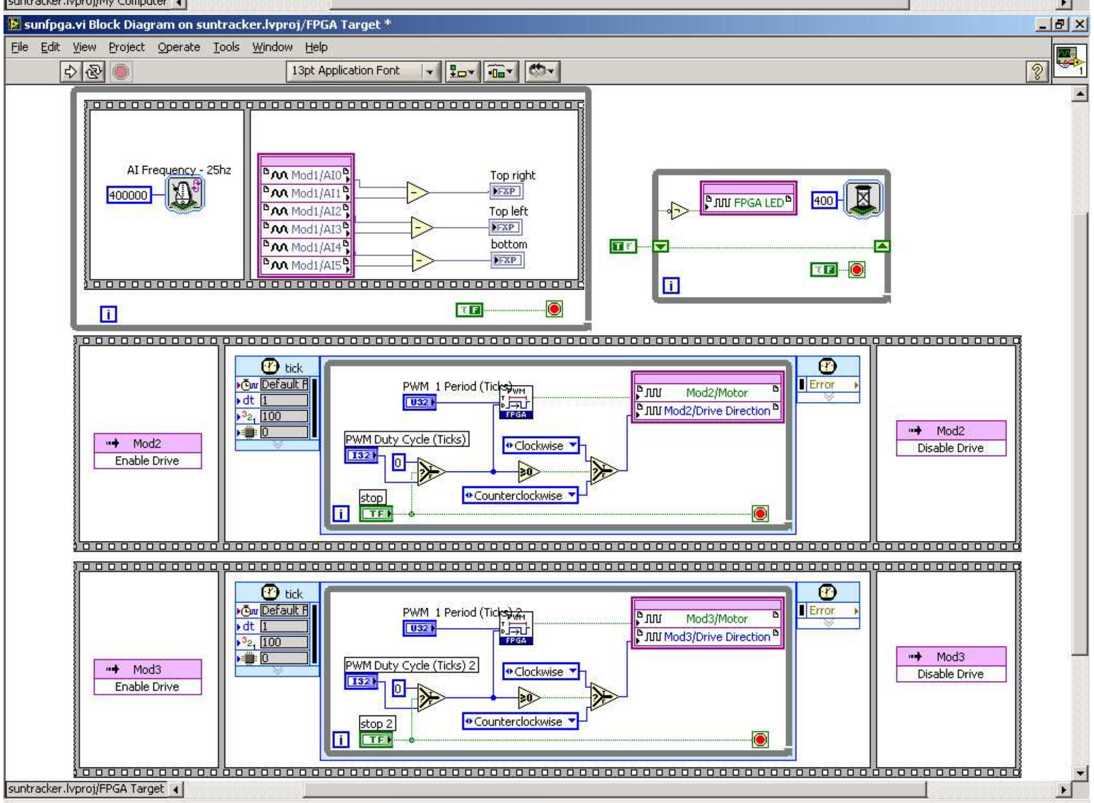
Labview Program Interface





Labview Program Block Diagrams





Photoresistor Curves Voltage vs Light Saturation

Supply Voltage 5 V

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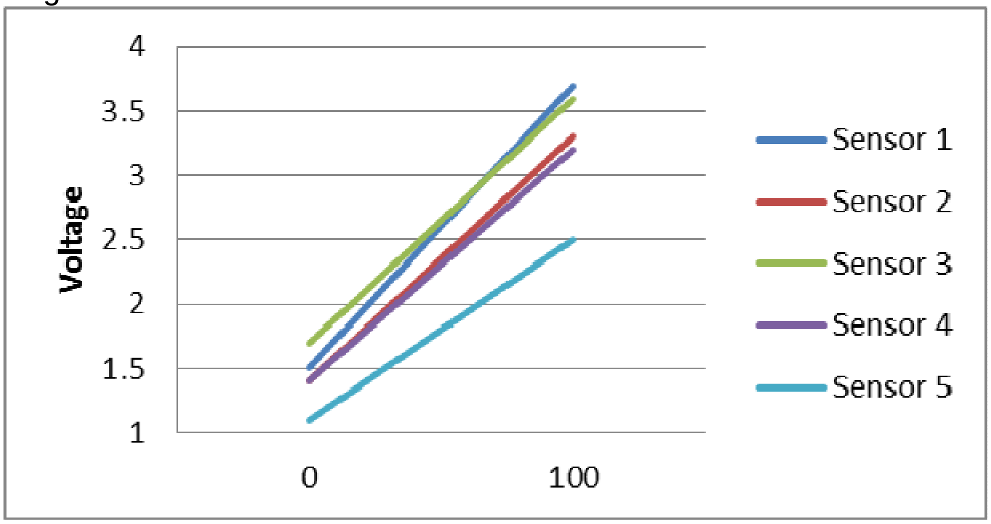
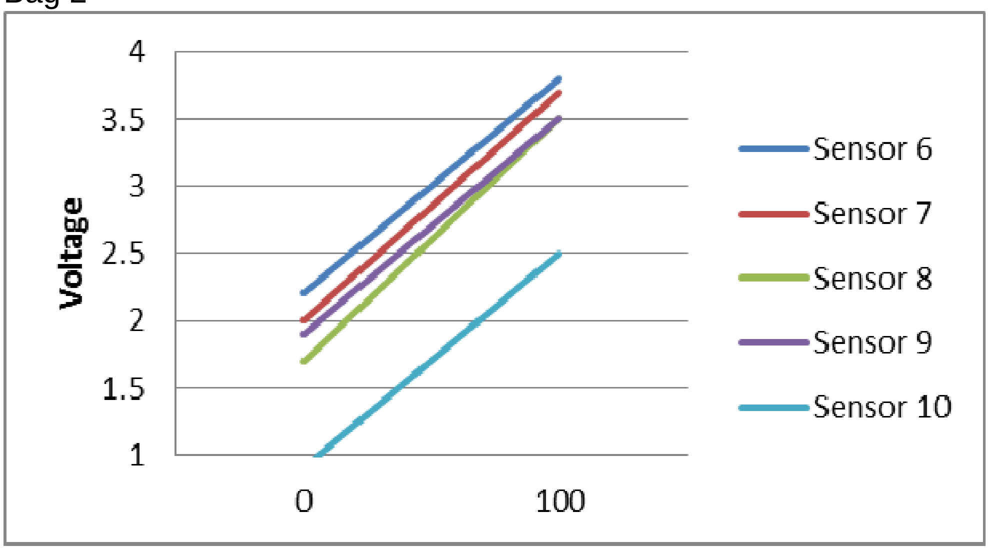


Bag 2



Supply Voltage 4 V

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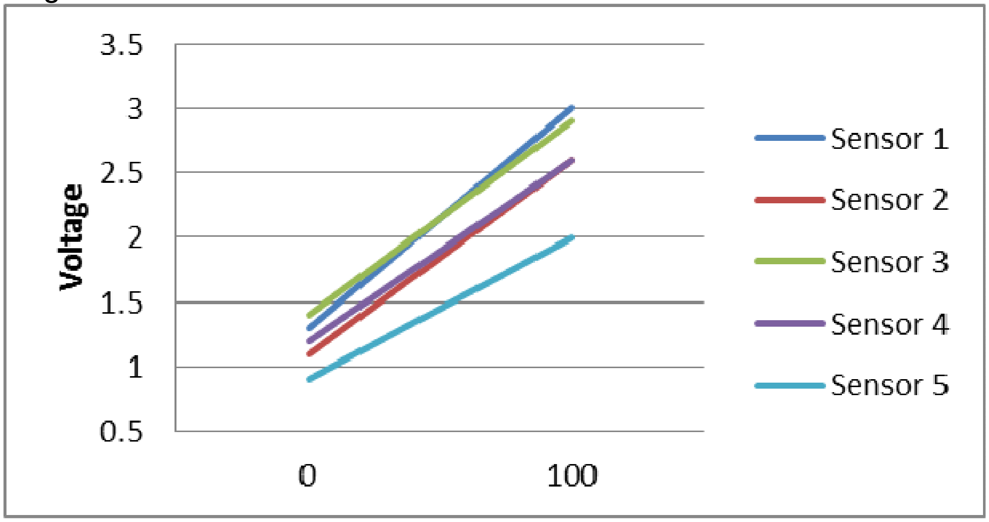

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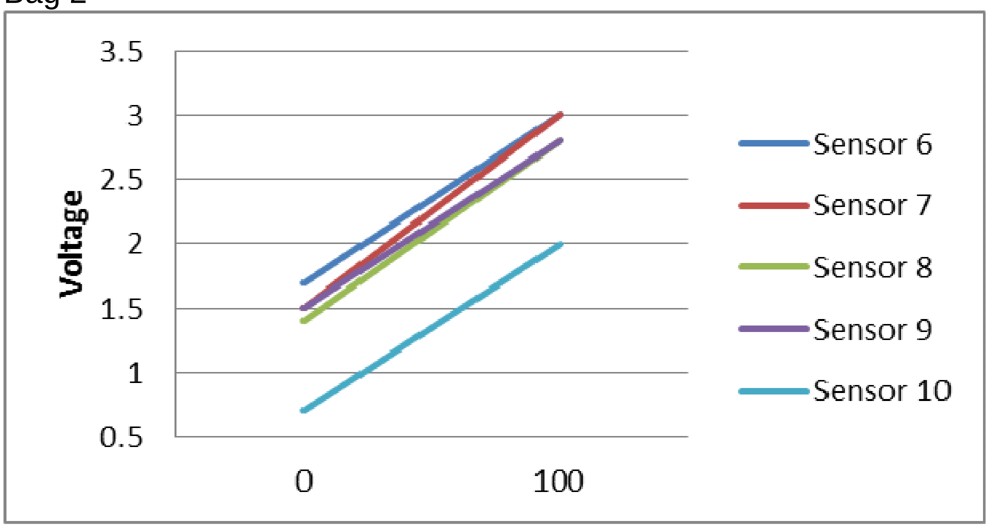

Supply Voltage 3 V

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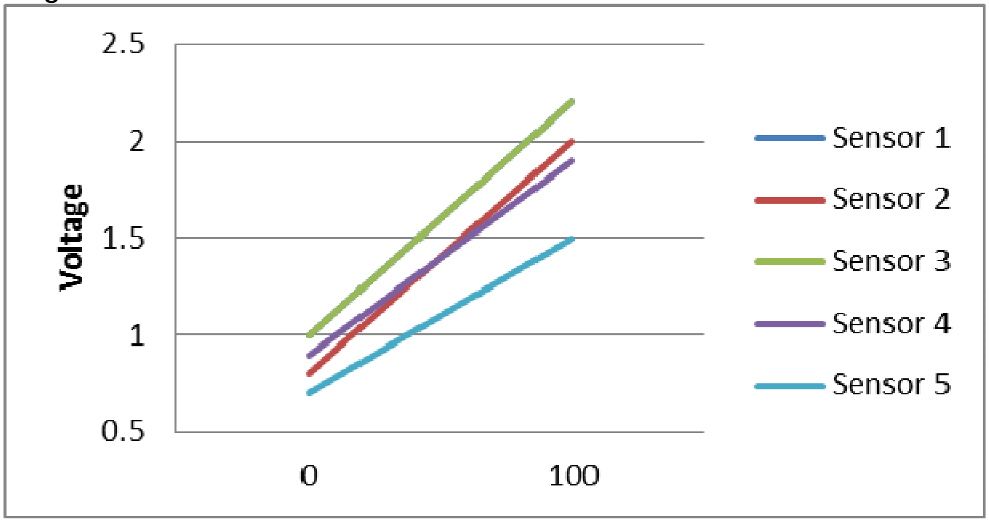

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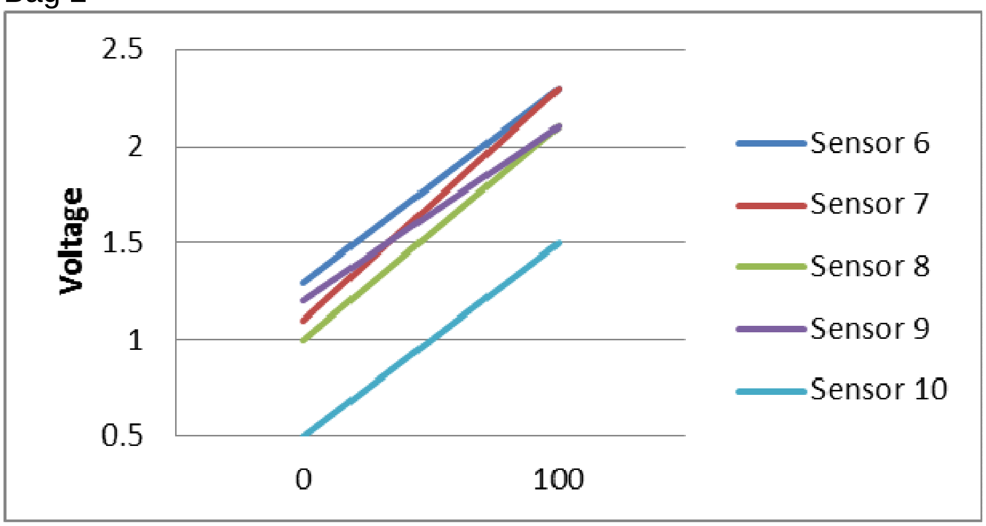

Supply Voltage 2 V

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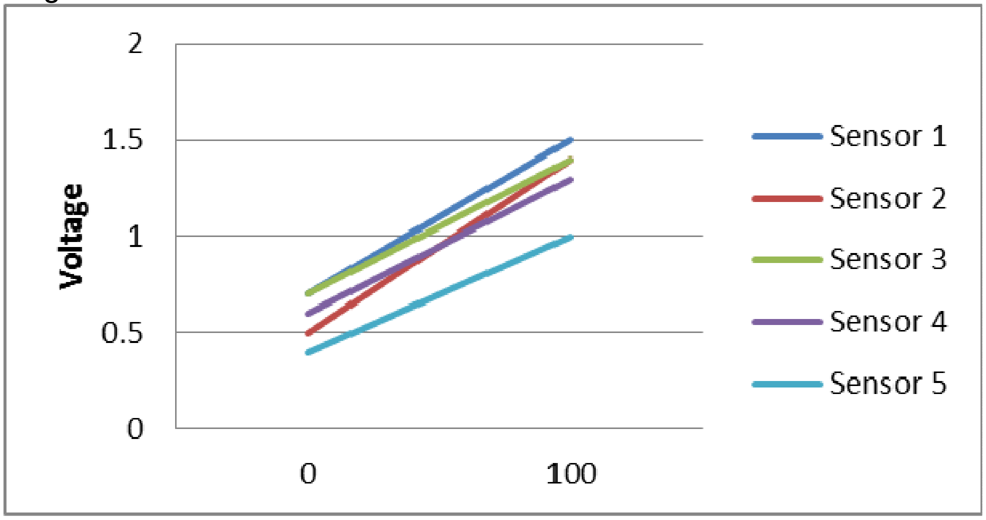

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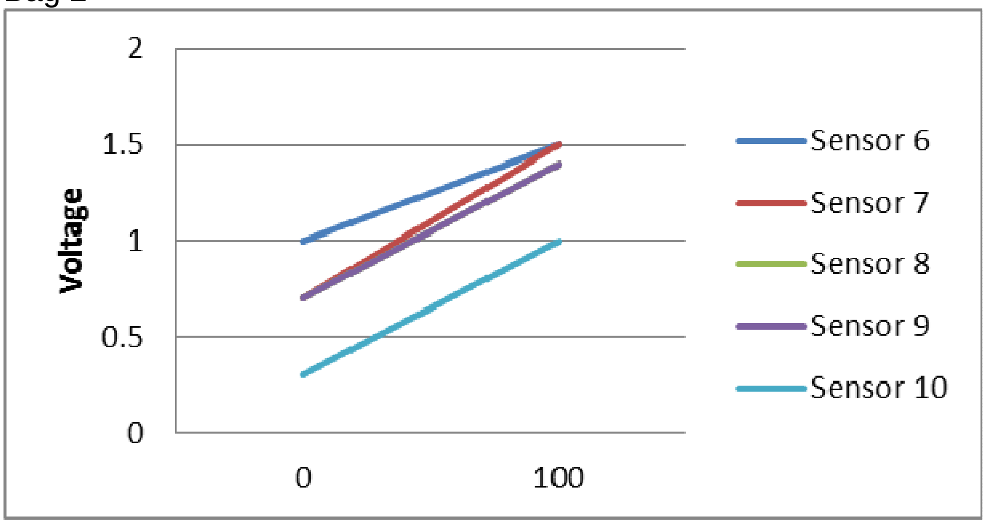

Supply Voltage 1 V

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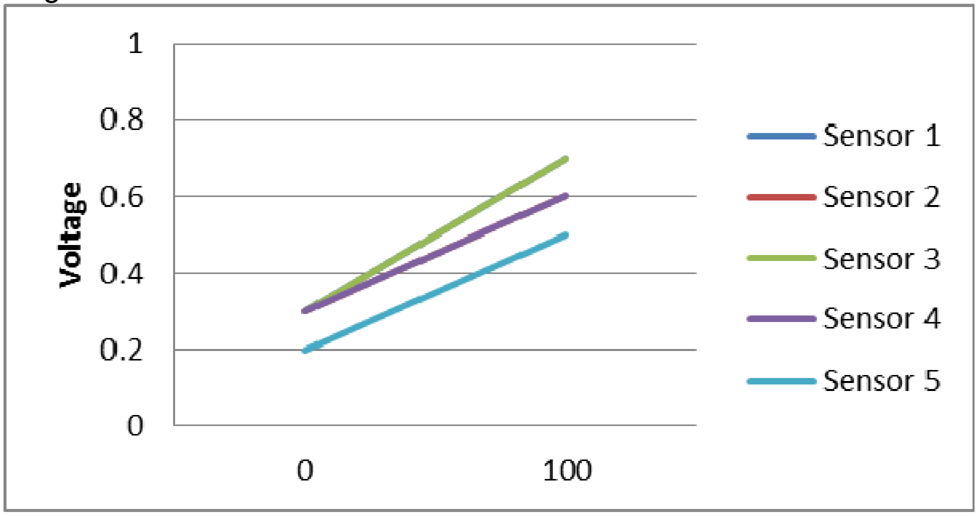

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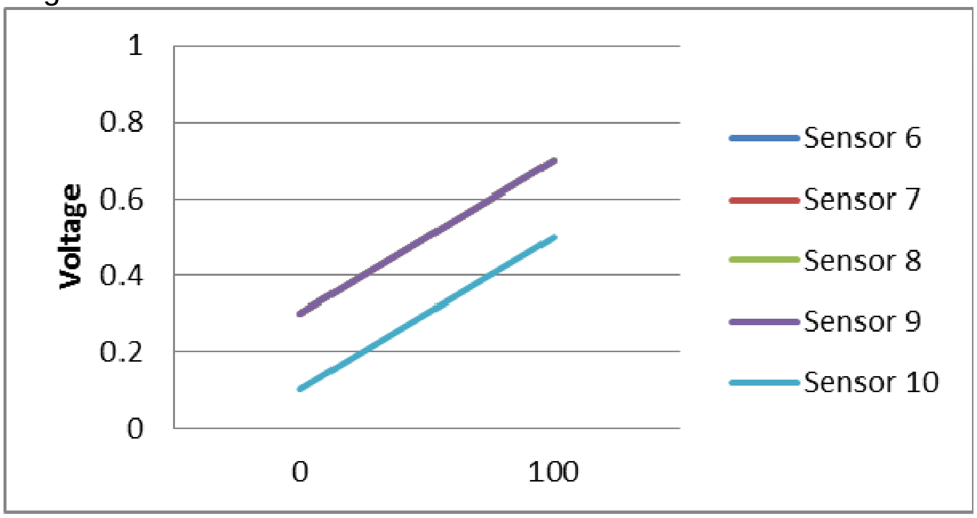

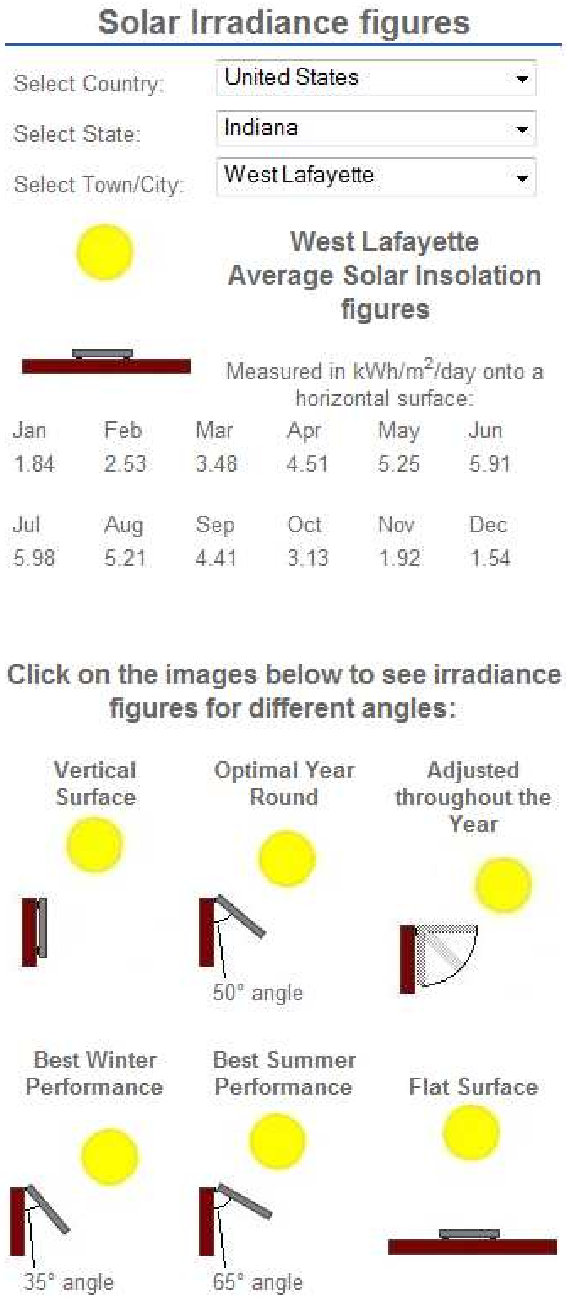
Solar Irradiance figures
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Select State: Indiana
Select Town/City: West Lafayette
West Lafayette Average Solar Insolation figures
Measured in kWh/m2/day onto a horizontal surface:
Jan 1.84
Feb 2.53
Mar 3.48
Apr 4.51
May 5.25
Jun 5.91
Jul 5.98
Aug 5.21
Sep 4.41
Oct 3.13
Nov 1.92
Dec 1.54
Click on the images below to see irradiance figures for different angles:
Vertical Surface
Optimal Year Round
50° angle
Adjusted throughout the Year
Best Winter Performance
35° angle
Best Summer Performance
65° angle
Flat Surface