Design of a Mechatronic Sensor System for Solar Energy Demand Based Monitoring

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***Abstract*—This study was able to design a mechatronic sensor system for solar energy demand based monitoring which consists of mechanical, electronic and software component implementation. The mechanical component consists of a flexible angular tilting mechanism that is able to vary the angle and orientation of the solar panels. The angular and orientation variations facilitated the discovery of applicable angles for a given energy demand to boost energy efficiency. The electronic component consists of a microcontroller system that uses current and voltage sensors. It was used to automatically acquire the actual solar energy absorbed by the panel for a given tilt angle and orientation. Finally, the software component consists of an algorithm that is used to trigger the recording of the sensors data at a specific period of time. The data stored can be used to analyze different scenario of solar energy demand. The result of the experiments showed that the mechatronic sensor system was able to gather solar power profile and total power produced for a given solar tilt angle and orientation. Initial experimental results show an energy profile shift of 115.67mins when comparing the East to the West facing solar panel.**

***Index Terms*—Demand Based; Mechatronics; Sensors; Solar Energy.**

I. INTRODUCTION

Renewable energy has great demand today due to the promise of having sustainable energy on earth. One of most popular renewable energy resource is solar energy. The use of photovoltaic (PV) solar panels is very popular to generate electricity from rural area and now even in the urban areas. One characteristic of PV solar panels is that the more exposure to solar energy, the more electric power will be generated Several factors should be considered in the placement of the solar panels like the tilt angle and its orientation to obtain the maximum energy especially for fixed photovoltaic panels.

Several researches [1],[2] have concluded that a south facing solar panel will produce maximum absorption of solar irradiation and they obtained the optimum tilt angle of solar panels for the south facing orientation. El Kassaby et al, determined the monthly and daily optimum tilt angles of solar panels for maximum energy absorption. While the study of Fidel Diaz et al [2], simulated the optimum solar panel tilt angles in the Philippines for a panel facing south. Also, an experimental setup was implemented to verify the absorption of irradiation from the sun for varying tilt angles. In their research, they were able to conclude that monthly and quarterly tilt adjustments would achieve better energy gains.

However, Cabuk and Naraghi [3],[4] correlated hourly cooling load consumption of a typical municipality in New York with the solar panel profile and the tilt angle. They obtained the energy profiles of the municipalities during the summer and arrived at the conclusion that during the summertime in August, the optimum solar panel orientation has an azimuth angle is 60° westward and a 25° tilt angle due to the energy demand profile of the building. A solar energy based system of tilting and orientation of solar panels is therefore needed to be studied.

Although there are some studies [5]-[8] that deals with the experimental acquisition of solar irradiance measurements. There is still no system designed to experimental verify energy profile of the sun at different angles and orientation to match the energy demand of a given building or community.

This study aims to design an efficient mechatronic sensor system that will record the power and energy profiles of the solar panels in different tilt angles and orientations. In this research, with the use of a microcontroller the sensor systems energy profile for a given tilt and orientation was recorded. The energy profiles obtained can be compared with actual energy demand profiles to obtain the best tilt angle and orientation for a given system. There were four solar panels used to test the system. The following sections will discuss the development of the mechatronic sensor system implemented.

II. SOLAR ENERGY DEMAND BASED SYSTEM

The tilt angle (β) and the orientation of the solar panel are the most essential variables in obtaining the maximum energy from the fixed solar panels. Figure 1 shows the orientation and tilt angle of fixed solar panel.

Previous studies such as El-Kassaby[1] mentions that the optimal face orientation for the northern hemisphere is south facing. El-Kassaby was able to create multiple equations to provide an estimate of the daily total extraterrestrial radiation given by the variable Id in units of (J/m^2).

$$I_d = \frac{24}{\pi} I_0 \left[1 + 0.034 cos\left(\frac{2\pi n}{365}\right)\right] \times [cos(\emptyset - \beta)\cos(\delta)\sin(h_{ss}) + h_{ss}\sin(\emptyset - \beta) sin(\delta)] \quad (1)$$

where:

β - tilt angle
ϕ – geographical latitude
δ – declanation angle
hss – sunset-hour angle

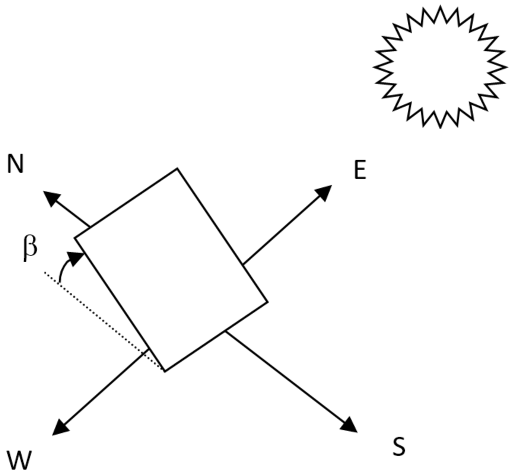

Figure 1: Solar Panel Orientation and Tilt Angle

The declination angle goes by the formula:

$$\delta = -23.45 \cos\left[(n + 10.5)\frac{360}{365}\right] \quad (2)$$

The sunset-hour angle is defined as:

$$h_{ss} = cos^{-1}\,[-\tan(\emptyset)\tan(\delta)] \quad (3)$$

Given these formulas, the optimal daily tilt angle of the solar panel is:

$$\beta_{opt,d} = \Phi - \tan^{-1}\left[\frac{h_{ss}}{\sin(h_{ss})}\tan(\delta)\right] \quad (4)$$

In the equations used above, all angles measured are in the unit degrees. The arctan quantity is an exception as it has to have a radian value as an input.

However, if we follow the maximum irradiation equations the energy profile produces a bell curve shape and might not follow the demand curve of a given situation. A sample energy demand curve in the Philippines is found in Figure 2 which shows that the energy profile system demand in the Philippines is skew to the right. Inorder to have maximum use of the solar panels, the energy profile produced by the panels should follow the demand of the system.

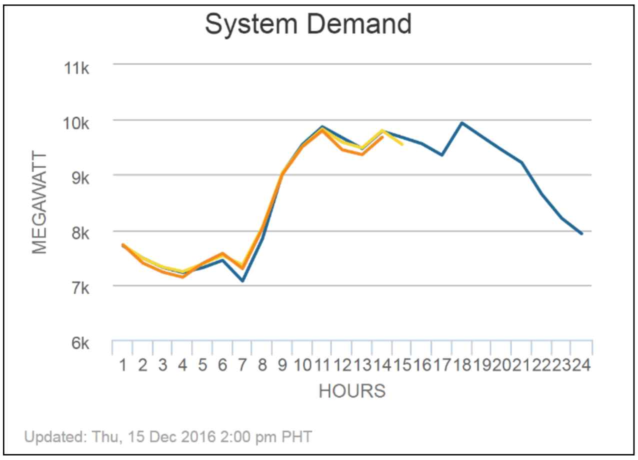

Figure 2: Sample Philippine System Energy Demand Profile (taken from http://www.wesm.ph/index.php)

In the past researches [3],[4], a demand based solar power tilt system is proposed so as to maximize the hourly cooling load consumption of a typical municipality in New York with the solar panel profile and the tilt angle. Dr. Naraghi obtained the energy profiles of the municipalities during the summer and arrived at the conclusion that during the summertime in August, the optimum azimuth angle is 60° westward and a 25° tilt angle.

The tilt angles and the orientation of the solar panel are the most essential variables in obtaining the maximum energy from the solar panels. This is caused by the sun's position in the sky and its rays hitting the solar panel. It is therefore important to build a mechatronic sensor system that will experimentally verify the solar energy profile for a particular tilt and orientation that will match application of the solar panels.

III. Methodology

In this section, the methodology adapted to create the mechatronic sensor system will be discussed namely: the mechanical, the electronic and the software components. These parts will all be essential in understanding the system as a whole. The methodology in the creation of the new mechatronic sensor system follows the flowchart in Figure 3. Each of the stages will be discussed accordingly.

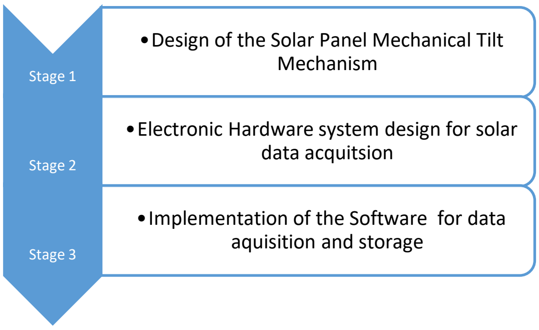

Figure 3: Flowchart of the Methodology

A. Mechanical Component

The solar panel used for the set-up are four 20 watt solar panels with the ratings of 17.7 V and 1.13 A at full load. A mechanical tilting mechanism was used to change the different tilting angles of the solar panel and to be able to change the orientation from the primary and secondary angles.

The actual tilting mechanism created is shown in figure 4 which provides accurate angle positioning. The range of the tilt adjustment is from -30° to 50° and was designed to accommodate 1° adjustments within the specified range. The mechanism has slots to lock at a desired tilt angle. Every slot in the mechanism corresponds to a degree within the range. A roll axis was also used to correct the horizontal level of the solar panel. This part also connects the tip of the base-pole and the tilting mechanism.

Figure 4: Actual Tilting Mechanism

B. *Electronic Component*

The solar panels will then be connected to the solar sensor measurement device. The measurement device box in figure 5 contains all the components needed in obtaining different measurements such as the voltage and current. It also houses the sensors, the resistors and microcontroller used.

Figure 5: Solar Measurement Device

Figure 6 shows the schematic diagram of the electronic system. The energy and power absorbed by the four solar panels was sensed through current and voltage readings. The current sensor used is the ACS71x current sensor. This current sensor used has a rating of up to 5A which is more than what is needed for the 1 A given out by the solar panels The resistor loads were designed at maximum load that can be connected to the solar panels to maximize the energy.. The resistor values used are to ensure that the solar panels would not be damaged because of over current. These resistors when installed should not be close to each other because it may heat up and burn if done so.

A resistor voltage divider was used in the system since the microcontroller used is rated only at 5 V maximum input, the 20 V input from the solar panels should be stepped down so that the microcontroller would be able to read it and not be damaged. The Arduino Mega 2560 Microcontroller was used to process all the sensor information and store all information to an SD card. Female to female headers are used to connect the different hardware needed to the microcontroller board.

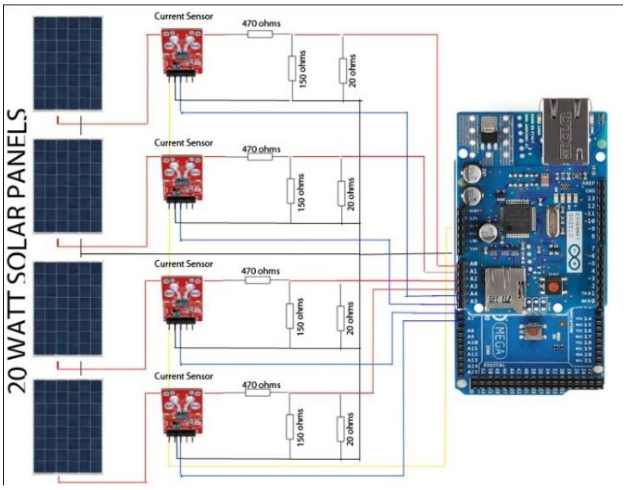

Figure 6: Schematic Diagram of the Electronic System

C. *Software Component*

The software in the microcontroller was created for the solar sensor measurement system using C programming with the different functions from Arduino IDE. Multiple libraries were used to help aid with the research. The following are the libraries used are spi.h, time.h and SD.h. These libraries are for the SD card connection, time stamp and SD card function respectively.

Figure 7 shows the flowchart of the software. The program consists mainly of two parts: the set-up and the loop. The set-up is where the variables are declared and where the sensors are initialized. The loop on the other hand is where the bulk of the program is located. A for loop is used to run the code for every solar panel. The for loop adds and goes back to zero when the data from the fourth solar panel is recorded. It obtains the voltage and current of the panel, it computes the power, the records the data. The analog read function is used to obtain the voltage and current values. The analog read function reads the voltage levels of the current sensor and the voltage divider circuit. These values will be mapped from 0-1024 depending on the level of the voltage. For example, the microcontroller read that the voltage is 2.5V, it would give out the voltage of 512. The map function of Arduino is used to convert these raw values back to their original voltage values and multiplied to obtain the real voltage that comes from the solar panels. This technique is also used in the current sensors.

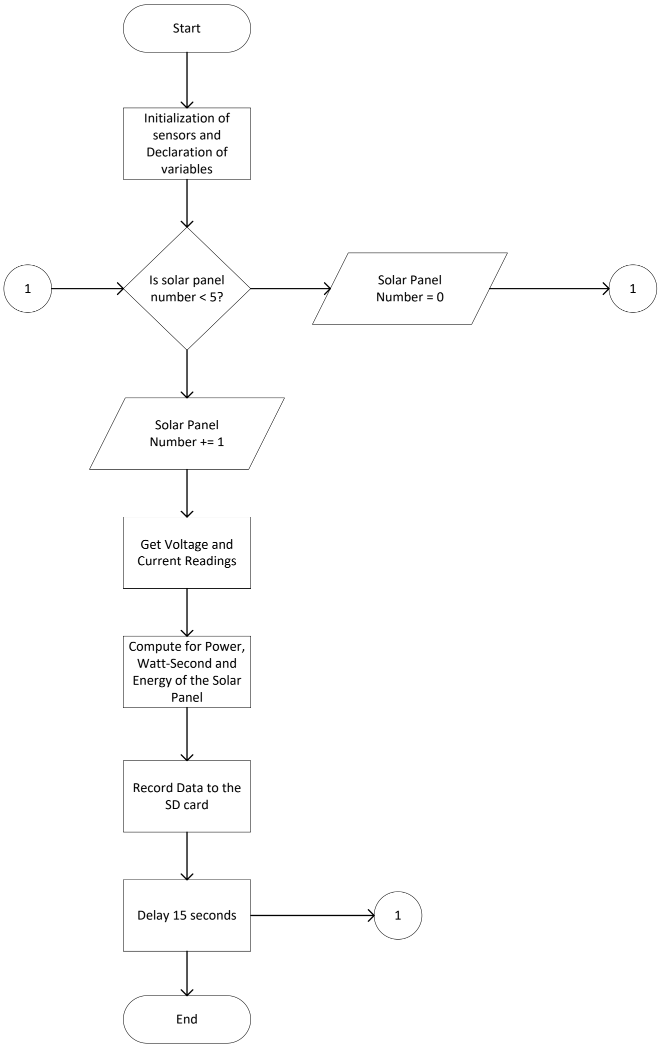

Figure 7: Software Flowchart

Different variables such as power and energy are then computed using the obtained voltage and current values. After computing all the variables, it will then store the data to the sd card. The time interval it takes to get the voltage and the current readings are 15 seconds per panel. This means that in one minute, all panels would record a reading and the time interval for the readings of a panel would be one minute. The timing interval was coded using the function delay(). The delay() function will do nothing for a specified time set by the user in milliseconds and continue the program after so. It does this for all the solar panels and starts again.

Figure 8 shows the mechatronic sensor system set-up with four solar panels facing at different orientations. The steel box below is the enclosure of the system which serves as the housing for the electrical components.

Figure 8: Mechatronic Sensor System

IV. Results

The data obtained using the mechatronic sensor system for an energy demand based system is shown in this section. The first part discusses the controlled set-up to ensure correct performance while the second part discusses the initial solar measurements using the mechatronic sensor system with four different solar panels with varied orientation.

A. Controlled Set-up

The first test of the mechatronic sensor system is using a DC power supply to simulate the voltage of a solar panel. It is also used to control the voltage going into the system. The current limit of the dc supply is at 1 ampere to mimic the output of the real current of the solar panels. Figure 9 shows the graph of the power vs time using the DC power supply. It shows that as when the power input is varied, the measured power corresponds with minimal error.

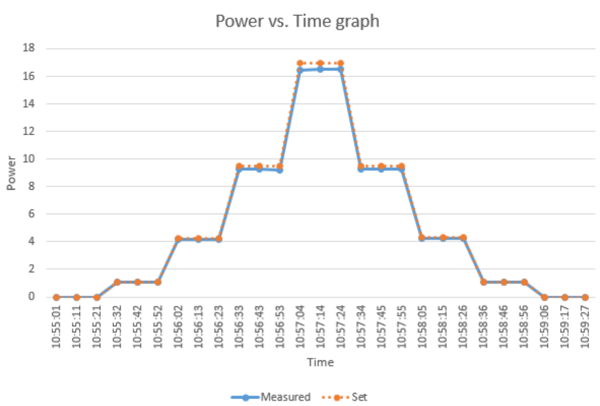

Figure 9: Power Measurement using a DC power supply

B. Actual Set-up

To obtain correct and accurate data, there is a need to calibrate the sensors. Calibration was done by measuring the voltage across the panels using a voltmeter and measuring the current by connecting the ammeter in series before entering the system. The voltage and the current is then verified with the voltage and current measured by the system. Variations with the multiplier are then made depending on the error of the system.

Figures 10 to 13 below shows a day of data for the four solar panels using the system made. This was recorded during a sunny day on the 24th day of August. During this time, the tilt angles of the panels were at 45°.

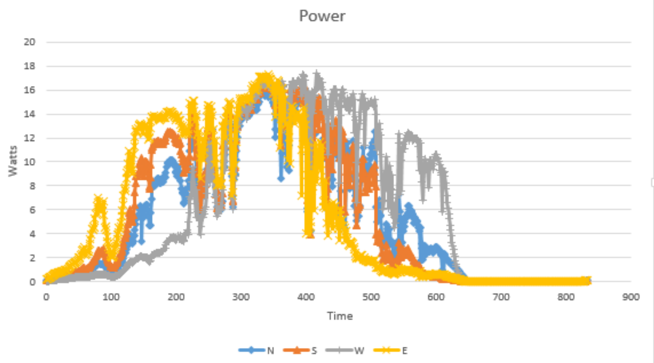

Figure 10: Power measured by the system

Figure 10 shows the data obtained using the four solar panels in one graph. The different colors show the different orientations of the panels. There are fluctutations from the graph because of the clouds that may have passed during the time duration which causes blockage of light from the sun. The suceeding graphs would analyse the difference in time shift for different orientations. In the suceeding data to be presented, the east facing panel will be compared with the other orientations since the sun rises from the east.

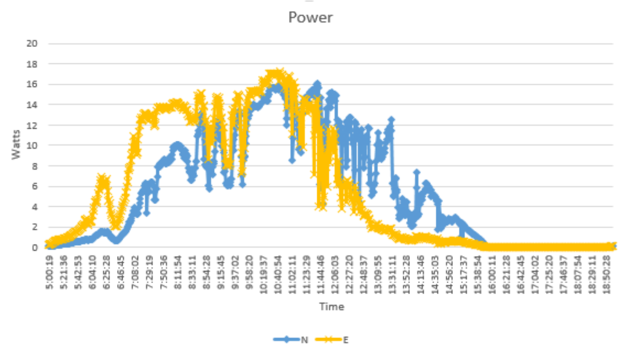

Figure 11: East vs North Solar Panel Profile

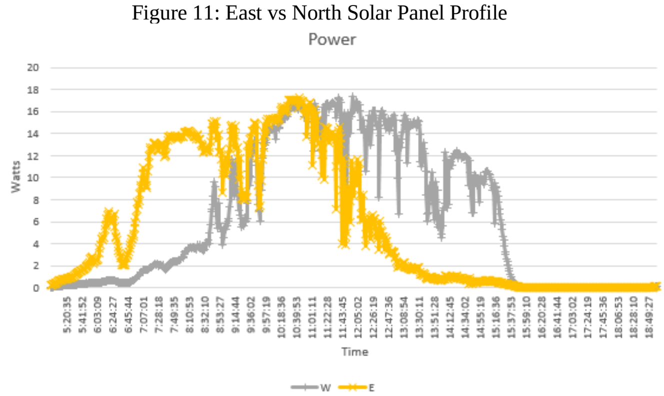

Figure 12: East vs West Solar Panel Profile

Figure 11 shows the North and East solar panels. It can be seen from the graph that there is a shift between the two orientations. Setting the testing point at 7, 10 and 13 watts, it can be observed that there is an average time shift 58.33 minutes between the two. The east facing solar panel has a graph of a profile skewed to the left. This is because of the fact that it would be the first orientatin to receive sun light. The north facing solar panel on the other hand has a profile that settles in the middle since it has a maximum power profile during noon time.

Comparing the east and west power profiles in Figure 12, It can be seen that there is a large shift between the two orientations. It is because they are the complete opposites of each other. An average of 115.67 mins shift between east and west panel was recorded. The west graph has a profile skewed to the right because the sun sets at the west.

Figure 13: East vs South Solar Panel Profile

In Figure 13, the east and south solar panel profiles are not far off from each other. For the day in August, the average time shift of only 21 minutes was recorded. Some factors that cause this small shift maybe attributed to the diffusion of the solar rays and the movement of the clouds.

Table 1
Average Time Shift compared to East Power Profile

Panel Orientation	Power Absorbed 7 watts	Power Absorbed 10 watts	Power Absorbed 13 watts	Average Time Shift
North	45 mins	63 mins	67 mins	58.33 mins
South	18 mins	20 mins	27 mins	21.67 mins
West	104 mins	122 mins	121 mins	115.67 mins

Table 1 tabulates the average time shift of the other panels compared to the East Power Profile when the different solar panel orientations reach the power of 7, 10 and 13 watts. This is essential to know the different time shifts of the different orientations of the solar panel.

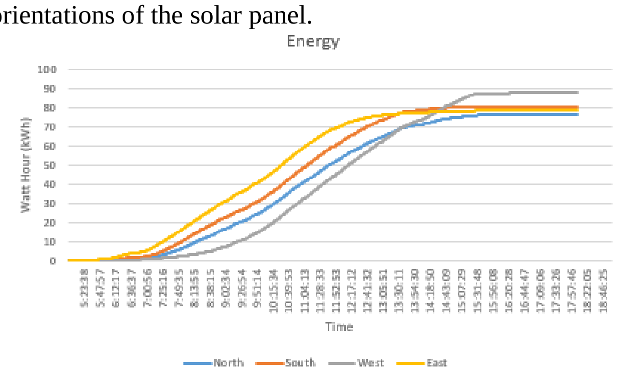

Figure 14: Power Produced by the Solar Panels

The power produced in W-hr for each panel was obtained by multiplying the time factor with power. Adding all the values gives us Figure 14. For this sample data, the west facing solar panel obtained the most energy among the four panel orientations of about 90 W-hr.

V. Conclusion

In conclusion, a new mechatornic sensor system was designed for a solar energy demand based system. The system was able to generate a demand based power and power production graph that could be used to compare with the demand of the system were the solar panels are installed. The data presented shows that the research was able to successfully obtain the demand based profiles for several solar panels in different orientations. This is essential to understand the maximum power and profile that a solar panel can give for a certain profile. In the future, we will compare the obtained profiles with the existing demand needs of a particular building or community to get the best solar angle and orientation for a given demand.

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