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Automatic dual-axis solar tracker system using Image Processing

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ABSTRACT

Solar energy is the most inexhaustible, renewable source of energy known to humanity. The energy extracted from photo-voltaic or any solar collector depends on solar irradiance. For maximum extraction of energy from the sun, the solar collector panel should always be normal to the incident radiation. Solar trackers move the solar collector to follow the sun's path and keeps the orientation of the solar collector at an optimal tilt angle. Solar tracking system improves substantially the energy efficiency of photo-voltaic panel. The aim of this project is to develop an Automatic Dual Axis Solar Tracker System with Image Processing in order to improve the efficiency of the solar panels.

Keywords: *Image Processing, Raspberry Pi, ATmega328 Microcontroller, Polyurethane.*

1. INTRODUCTION

The demand for electricity and its price is continuously increasing over time. Solar energy has become a preferred alternative to meet the increase in electricity demand because of its ubiquity, abundance, and sustainability. Regardless of the intermittency of sunlight, solar energy is widely available and is completely free of cost.

Energy conversion here is with the help of a photo-voltaic system. A photovoltaic system is a power system designed to purvey usable solar power employing photo-voltaic cells. It consists of an arrangement of different components, with solar panels to absorb and convert sunlight into electricity, a solar inverter to switch the electric current from DC to AC, a charge controller to make the energy from the source constant, as well as mounting, cabling and other electrical accessories to set up a working model.

Among all renewable systems, the photo-voltaic system is the one that has a great chance to replace conventional energy resources. The solar panel directly converts solar radiation into electrical energy. Solar panels are mainly made from semiconductor materials. Si is used as the major component of solar panels, which is 24.5% efficient.

Research conducted by [4] shows that the current obtained from solar cells is greatly influenced by the angle at which incident rays strike the cell surface. From figure 1, it can be stated that to maintain maximum power output from a solar array, the angle of incidence must be held at zero degrees. Hence, the array must constantly face the sun. This requires a tracking system that can continuously align the array into the desired position. This can be done with the help of solar trackers.

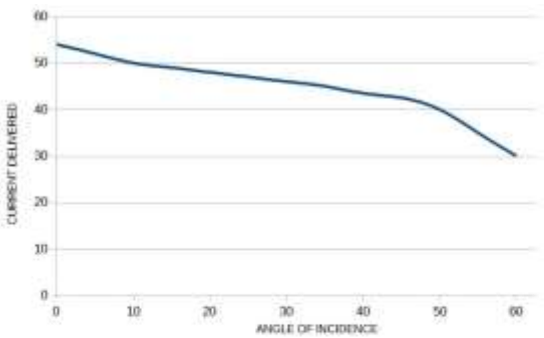

Figure 1 - Current output vs angle of incidence.

A solar tracker is a device for orienting the solar photo-voltaic panel or concentrating solar reflector or the lens towards the sun. Solar-powered equipment works best when pointed at or near the sun, so a solar tracker can increase the effectiveness of such equipment over any fixed position. The tracker will enable the panel to follow the path of the sun and produce more power as it absorbs more sunlight. Concentrators, especially in solar cell applications, require a high degree of accuracy to ensure that the concentrated sunlight is directed precisely to the powered device. In commercial terms, there are two types of solar tracking systems - single axis and dual axis. Single-axis solar trackers can either have a horizontal or a vertical axis. The horizontal type is used in tropical regions where the sun gets very high at noon, but the days are short. The vertical type is used in high latitudes where the sun does not get very high, but summer days can be very long. Dual-axis solar trackers have both a horizontal and a vertical axle and so can track the sun's apparent motion exactly anywhere in the world. This type of system is used to control astronomical telescopes. Dual-axis trackers track the sun both east to west and north to south for added power output and convenience. By using a dual-axis solar tracker, it can capture the maximum sunlight in two movements that is elevation and azimuth and at the same time, it can receive the full capacity of lux. Dual-axis tracking increases the electricity output by as much as 35 percent to 40 percent. To get the maximum intensity of light and zero voltage difference (error degree) the position of the panel must always be perpendicular to the light source [5]. The position of the sun will change from the position of the installed solar tracker and make the panel no more perpendicular to the sun which affects the output power. Thus dual-axis solar tracker makes the movement of the solar panel be always perpendicular to the sun.

2. METHODOLOGY

The azimuth and elevation are the two coordinates that define the position of a celestial body (sun) in the sky as viewed from a particular location at a particular time. Digital image processing is carried out before the calculation of the required angles to guide the solar tracker. Image processing is done using MATLAB software, to convert the image into digital signals corresponding to the position of the sun. After calculating the required angles, signals are sent to the microcontroller to move the sun to the point of maximum solar irradiance (the centre of the cross mark). The tilt and pan movement of the PV array is completed with the help of two Stepper motors connected.

A Solar tracker is an automated solar panel which actually follows the sun to get maximum power. Even though a fixed panel can be set to collect a high proportion of available noon-time energy, significant power is also available in the early mornings and late afternoons. This misalignment with a fixed panel becomes ineffective to collect a reasonable proportion of the available energy. For example, even when the Sun is only 10° above the horizon the available energy can be around half the noon-time energy levels (or even greater depending on latitude, season, and atmospheric conditions). Thus, the primary benefit of a tracking system is to collect solar energy for the longest period of the day, and with the most accurate alignment as the sun's position shifts with the season.

2.1 Inverse Square Law

The illumination upon a surface varies inversely as the square of the distance of the surface from the source. Thus, if the illumination at a surface 1 meter from the source is I units, then the illumination at 2 meters will be one by fourth of I, similarly, 3 meters will be I/9 and so on.

The inverse square law operates only when the light rays are from a point source and are incident normally upon the surface.

$$\text{illumination} = \frac{\text{candle power}}{\text{area}} \qquad (2.1)$$

therefore,

$$E = \frac{I}{D^2} \qquad (2.2)$$

2.2 Lambert's Cosine Law

Lambert's Cosine Law states that "The illumination received on a surface is proportional to the cosine of the angle between the direction of the incident light rays and normal to the surface at the point of incidence".

This is mainly due to the reduction of the projected area as the angle of incidence increases.

$$E = E * \cos \Theta \qquad (2.3)$$

Combining equations 2.2 and 2.3, illumination on any horizontal plane is given by

$$E = E * \cos \Theta = \frac{I * \cos \theta}{D^2} \qquad (2.4)$$

where,

E = Illumination due to normal component of the light source (Lumen)
I = Luminous Intensity of light source (Candela)
D = Distance of the light source from the plane (m^2)
Ɵ = The angle of incidence of the light source (Degrees)

3. WORKING PRINCIPLE

The block diagram of the proposed system is shown in figure 2. The system mainly consists of an electrical part and a mechanical part.

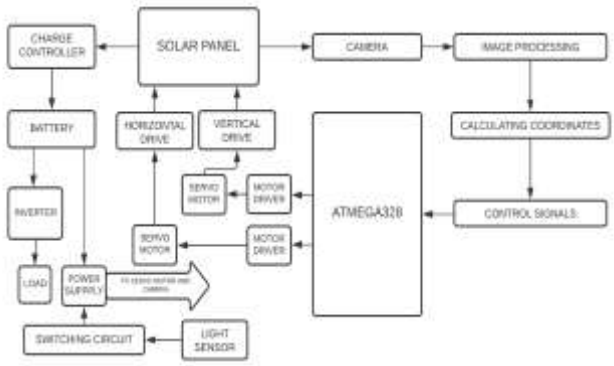

Figure 2 Block diagram of the proposed system.

The electrical part of the system is responsible for the generation of electricity from the solar panel. The detailed block diagram is shown in figure 3. The solar generation circuit mainly consists of the solar panel, solar charge controller, battery, inverter, transformer and the loads. Since the supply from the solar panel is unstable, a charge controller is used to stabilize the supply. Another function of the charge controller is to charge the battery. The DC loads of the system can be directly connected to the battery. For the supply of the AC loads, an Inverter is used to convert the 12 V DC to 12 V AC. Finally, the transformer steps up the 12 V to 230 V AC to give supply to the AC loads.

The mechanical part of the system is responsible for the movement of the panel to track the sun. It consists of the ATmega328 microcontroller, motor drivers, stepper motors, and the horizontal and vertical drive system. The microcontroller accepts the image processed inputs from the computer and gives signals to the motor drivers. Here, two drivers are used to control the horizontal and vertical axis movement of the solar panel. These motor drivers then give signals to drive the motors which makes the panel align to the desired position of the sun. The mechanical system is implemented both in Proteus and Simulink and is found to be working.

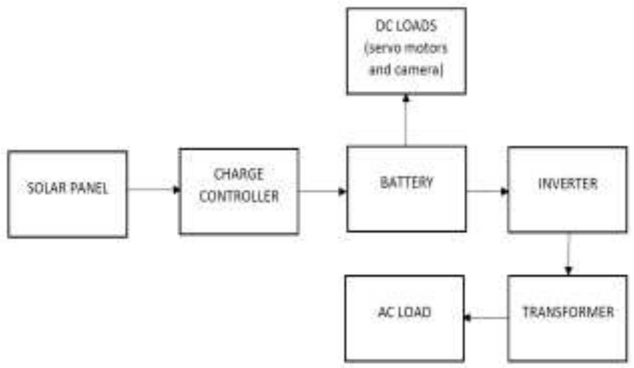

Figure 3 Block diagram of solar generation.

The main control circuit of the project is the image processing software. Matlab software is used to process the image. The sun's image is captured in the camera and is compared with the desired position. The coordinate of the sun is calculated with the image processing technique to generate the desired control signals. The control signals will be the input of the microcontroller. Conventional techniques include the control technique using LDRs (Light Dependent Resistors). The image processing technique is employed to give more accurate results which in turn improve the efficiency of the solar generation.

The image processing is done in Matlab and the code is embedded in the Raspberry Pi 4 microcontroller. The camera connected to the Raspberry Pi captures the picture for image processing. Matlab then processes the image and produces the position coordinates. Using these position coordinates, the Raspberry Pi generates the desired control signals to the ATmega328 microcontroller to rotate the stepper motors. This aligns the panel to the desired position.

4. RESULTS AND DISCUSSION

The results of the various parts of our project are presented in this section.

4.1 Mechanical system

The first step of the system is the calculation of the solar coordinates using the process of image processing. Then the calculated solar coordinates are given to the input of the summer. The desired coordinates of the sun will be the midpoint of the Cartesian axis in the camera, which is the position coordinate (0,0). The difference in the position is the error in the system. This error signal is given as the input to the controller. The controller generates the signals to the motor which generates the desired torque. The torque moves the panel to the desired position. This process is repeated every 15 minutes until the desired position of the panel is reached. This is the basic approach of the mechanical system.

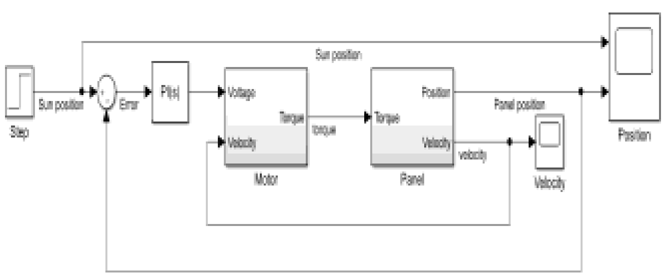

Figure 4 Simulation of the mechanical system.

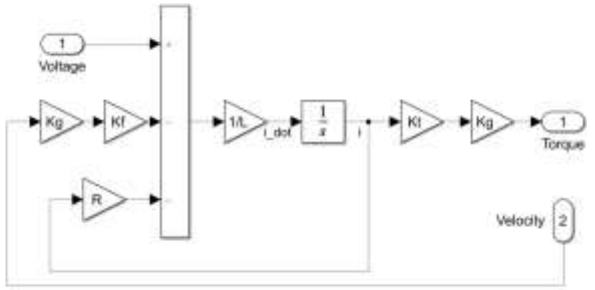

Figure 5 Motor block in the mechanical system.

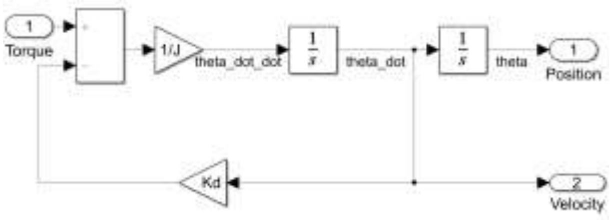

Figure 6 Panel block in the mechanical system.

The results from the scope are shown in figure 7 and figure 8. To ensure the proper working of the simulation, a step input is given as the position coordinates of the sun and the results are observed in the scope. It is shown by the graph in figure 7. When step input is applied at the time, t=1. The panel initially being at position zero begins to move at t=1. At the time, t=6 the panel finally reaches the position of the sun with a small overshoot. This overshoot can be neglected as the panel is moving very slowly.

In figure 8, the output from the velocity scope is shown. A spike is recorded in the curve at the time, t=1. This ensures that the panel starts to move when the signals are applied. After moving to the final position at a time, the t=6 velocity curve reaches zero. This shows that the panel is finally at rest as it aligns itself in the direction of the sun.

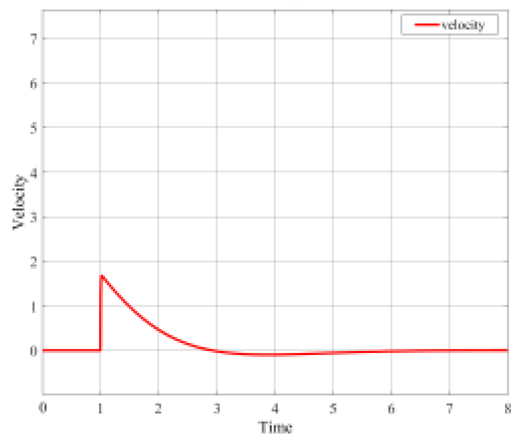

Figure 7 Velocity vs time graph.

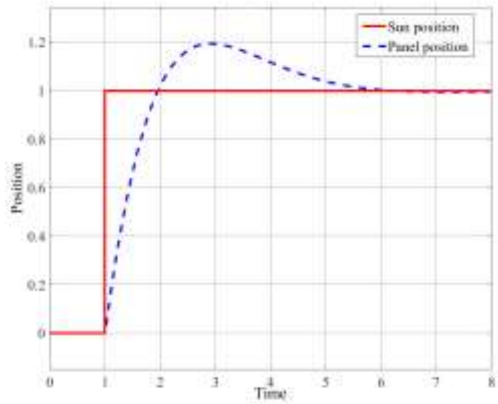

Figure 8 Sun and panel position vs time graph.

The simulation of the mechanical system is also done in proteus and is shown in figure 8.6. Here, image processing inputs are applied at digital pins 1,2,3,4 of the Arduino UNO. L293D motor drivers are used to moving the vertical and horizontal movement stepper motors.

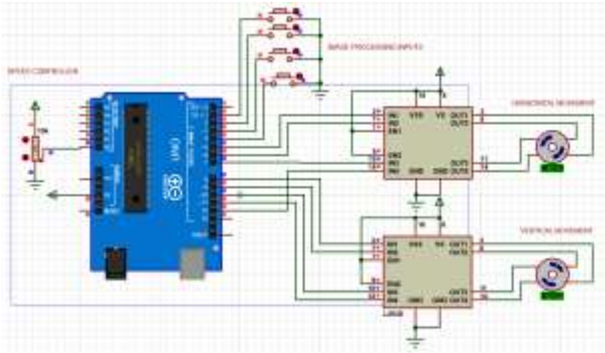

Figure 9 Simulation of the mechanical system.

Stepper motors are used so that a sufficient amount of torque can be produced with slow speed and less acceleration. This simulation is found to be working with a step angle of 18 degrees per pulse in the stepper motor. Here, for the sake of providing inputs from image processing and to simulate the experiment push buttons were used.

4.2 Solar charge controller

The main part of the circuitry is LM317T IC which is used to stabilize the unstable voltage supply from the solar panel. The output voltage provided by the IC is given to a voltage divider circuit to obtain the charging voltage of the battery. The transistor connected in series to the relay coil acts like a switch. When the battery reaches its pre-set cut-off voltage the Zener diode breaks down. This turns on the transistor. This causes supply through the relay coil and latches it thereby isolating the battery from the supply. When the battery voltage goes down from its cut-off voltage, the transistor turns off, breaking the current flow through the coil. This causes the relay to latch back to its initial position and allow the battery to be charged.

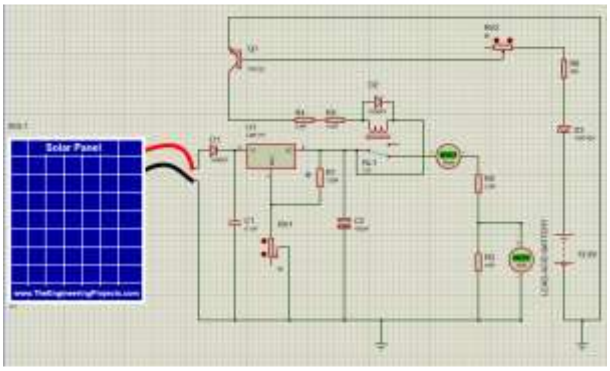

Figure 10 Simulation of the solar charge controller.

The solar charge controller circuit to charge a 12 V battery is shown in figure 10. The circuit is found to be working with an output voltage of 13.8 V and an output current of 0.29 A. The battery continues charging till its voltage becomes 13.8 V. When battery voltage goes above 13.8V, the relay switches its contacts, and battery charging stops.

4.3 Image processing

The Image Processing Toolbox of Matlab is used for processing the captured image. Since Processing Matlab code requires a good amount of CPU power Raspberry Pi chipset is used. The camera for capturing the image can also be integrated into the Raspberry Pi board. The code written in the Matlab script is sent to Raspberry Pi through the Matlab support package for Raspberry Pi hardware.

This program aims to find the coordinates of the origin point and sun. From that, we can find the direction to move the motors to make the sun's centre and origin coincide. The coordinates of the sun and origin point are calculated with the Image Processing Toolbox. The directions to move motors are given as the output.

The results obtained through image processing are shown below. The outputs from Matlab include an image pointing to the position of the sun and the coordinates of both sun and origin and also the direction of movement of the motor which is printed in the command window.

The results of two random positions of the sun are shown in section 4.2.1 and section 4.2.2.

4.2.1 Position 1

Figure 11 Identification of sun.

.

From Figure 11 we can identify that the position of the sun is in the 4th quadrant. So, the movement of the one motor should be downwards and the other towards the right which is shown in figure 12.

Figure 12 Matlab command window output.

4.2.2 Position 2

Figure 13 Identification of sun.

From Figure 13 we can identify that the position of the sun is in the 3rd quadrant. So, the movement of the one the motor should be downwards and the other towards the left which is shown in figure 14.

Figure 14 Matlab command window output.

4.4 Inverter

The circuit to convert the 12 V DC to 230 V AC is shown in figure 6.2. This circuitry is required to deliver power to the AC loads connected to the system. The heart of the circuit is the CD4047 multivibrator. It is used to produce pulses Q and $\overline{Q}$ simultaneously. The 10 and 11 Pins that are Q and $\overline{Q}$ are connected to the power MOSFET IRF540. This MOSFET acts as a switch. The multivibrator turns on and off the MOSFETs Q_1 and Q_2 simultaneously to give +12 V and -12 V at the transformer primary terminal. The transformer finally steps up the square wave to get 230 V at the secondary terminal which can be connected to the load. The circuit mainly involves the design of the Transformer, the power MOSFET, and the multivibrator.

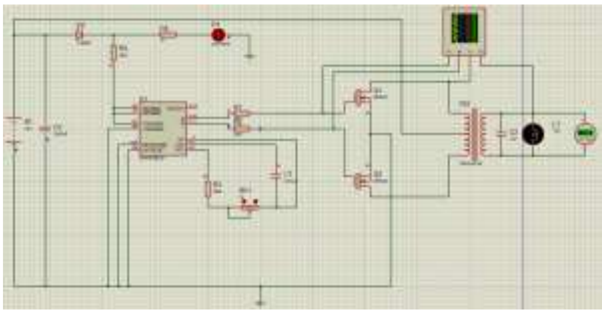

Figure 15 Simulation of Inverter.

The Simulation of the 12 V DC from the battery to 230 V AC to be supplied to AC loads is shown in figure 15. The simulation is found to be perfectly working. It is used to give power to a bulb.

Figure 16 shows the results from the oscilloscope connected to Q, $\overline{Q}$, transformer input, and output terminals. The positive half of the AC waveform is formed when Q is high and the negative half is formed when $\overline{Q}$ is high. The AC voltage has a frequency of 50 Hz. Therefore, the circuit can be used to charge AC loads.

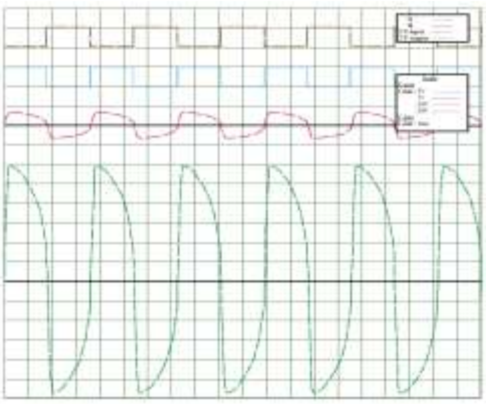

Figure 16 Output waveforms.

4.5 Switching circuit

The switching circuit using LDR and operational amplifier is shown in figure 17. Here, the battery is used to supply power to the operational amplifier, the relay coil, and the loads.

The operational amplifier act as a comparator. The operational amplifier 741 is used in this application. Typically, in a street lighting circuit the system, for automatic turn on, the system must turn on the supply during night. But here, the system must turn on the circuit during daylight and turn off the circuit during night. Therefore, the reference voltage is given in the inverting terminal of the operational amplifier. This reference voltage can be controlled by using a 1 kΩ potentiometer.

The sensitivity of the operational amplifier to the intensity of the light can be adjusted using this potentiometer. The LDR and another 1 kΩ resistor is connected as a voltage divider in the non-inverting terminal of the operational amplifier. When the voltage at in non-inverting terminal is greater than the inverting terminal, the output of the operational amplifier will be high. And when it is less than the inverting terminal, the output will be low. The voltage at the non-inverting terminal will vary with the intensity of light reaching the LDR. Therefore, the output of the operational amplifier can be controlled using an LDR.

During the daytime, when the intensity of light is sufficient to produce the desired solar power, the operational amplifier turns on the transistor. This energizes the coil of the relay and the relay contacts shift their position so that the battery supplies current to the load. When there is not sufficient sunlight, the output of the operational amplifier will be low. The sensitivity of the LDR can be controlled using the potentiometer which is connected to the inverting terminal of the operational amplifier.

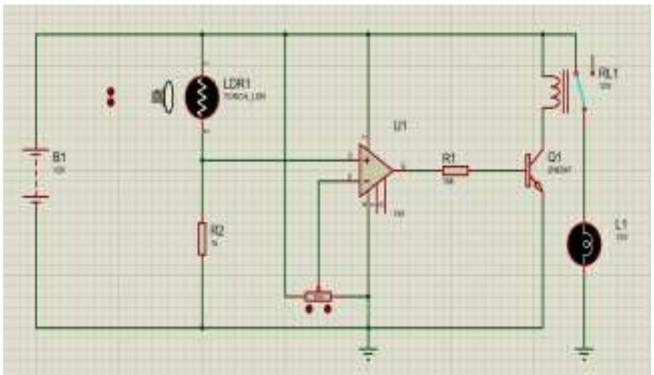

Figure 17 Simulation of LDR switching circuit.

When the sensitivity of the switching circuit is low, more intensity of solar radiation will be required to turn on the relay and thus powering the circuit. When the sensitivity is high, the circuit turns on even with the small intensity of light, even when solar power generation is not possible. It is undesirable. Therefore, the sensitivity of the system is adjusted to a moderate level for the optimal operation of the switching apparatus.

5. PROTOTYPE

Since the project is solar tracking in a two-axis system, a very effective model had to be developed which can move the panel in a dual-axis. For that, in the very beginning, a rough sketch of what the probable model would look like had been prepared. After that, a prototype of the model using cardboard was constructed since it would give a better visualization of what the model will look like. Finally, the model was constructed using a Polyurethane board (an alternative material for plywood).

Model Overview

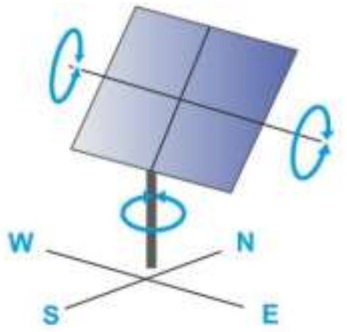

Figure 18 Two-axis movement.

The entire system relies on two different rotational movements in two different axes. For that purpose, the model is simplified into two different parts: the panel holder and the base. Each part of the base holds a stepper motor.

Working Mechanism

The prototype model moves in two axes with the help of two stepper motors. The motor with the medium rating is responsible for the movement of the panel and the motor with the higher rating is responsible for the movement of the panel holder. The upper part of the model (panel holder) tracks the sun linearly and the base is responsible for tracking the parabolic displacement of the sun. The movements are shown in figure 19 and figure 20.

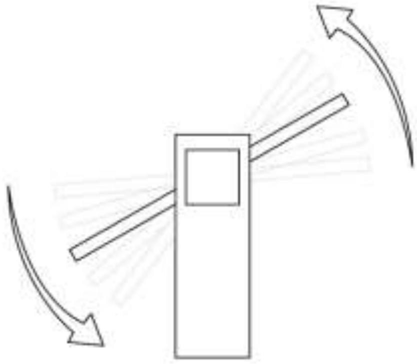

Figure 19 Movement of the panel.

Assembling the Model

The components of the prototype are shown in figure 21. The making of the prototype was from low-cost materials, keeping in mind to make the system affordable to all.

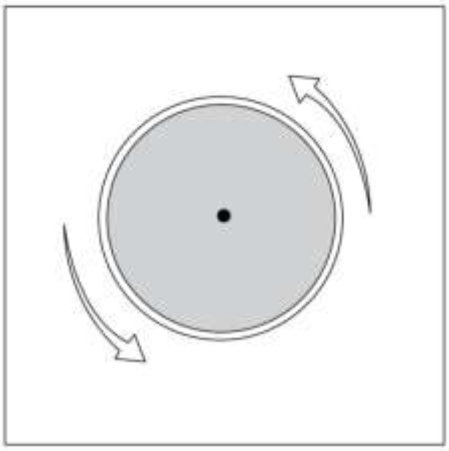

Figure 20 Movement of the base.

Figure 21 Parts of the prototype.

The Prototype of the above-proposed model was developed using a lightweight Polyurethane board, which is an alternative for plywood. A polyurethane board has to be the most fundamentally distinct plywood replacement in terms of sheer comparison with plywood. It is not susceptible to water damage or fracturing due to moisture absorption, since it is made of plastic. It is also surprisingly lightweight and if reinforced with fiberglass, can have equal longevity. The reinforced polyurethane board is just as suitable as any piece of plywood for structural and semi-structural employment.

Figure 22 and figure 23 show the front view and the side view of the prototype model. Ball bearings are provided for the tilt and span movement of the panel board. The base dimension is 23 cm x 30 cm. The height of the system is 40 cm. The overall weight of the system is 1.5 kg.

6. CONCLUSION

Solar energy has enormous potential as a source of renewable energy for meeting the strong and ever-growing energy demand in the world. In the last

Figure 22 Front view of the prototype.

Figure 23 Side view of the prototype.

few years, significant development has taken place in various solar energy systems for exploring their use as a source of renewable energy.

The different types of PV systems are fixed and tracking systems. The tracking systems can track the sun's trajectory for the day, capture much more solar energy and thus produce substantially higher output power. Dual-axis solar trackers are observed to be more efficient in comparison to single-axis solar trackers as they are capable of extracting more radiation during the day.
The main contributions of this work are the development of a dual-axis solar tracker prototype that uses image processing by Matlab to calculate the optimum position. The Arduino helps to make the circuit less complex. The model of the dual-axis solar tracker system is developed using Proteus. The simulation of the system has been achieved via the same. The desired results have been obtained.

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