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International
Journal
Of Modern Engineering Research (IJMER)

Development of a Smart Mechatronic Tracking System to Enhance Solar Cell Panels Performance

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Abstract: *Two degree of freedom Mechatronic solar tracking system was developed in the present study to improve the performance of photovoltaic cell panels. The present tracking control algorithm was applied on a small prototype, simulating a solar cells panel tracking system, designed and constructed in this work. The Mechatronic tracking hardware section consists mainly of a commercial arduino micro-controller with built in, two servo motor drivers, data input/output, and micro processor modules. Other components of the tracking hardware are, servo motors actuators and four LDR light intensity sensors. A feedback control soft ware program, designed and constructed in the present work, enables the solar tracker to automatically compensate for the sun location's change to enhance the PV cells efficiency. The LDR sensors are employed to continuously detect the sun rays intensity at four, light exposed isolated positions, representing up-right, up-left, down-right, and down-left sides of the solar panel. LDRs data is hence sent to the control software. The data is used to decide proper actuation actions and send them to the servomotors to redirect the PV cells panel perpendicular to incident sun rays. Sensors and actuation signals are exchanged via the in/out data module of the Arduino package. Results of the present experimental work show that using the present tracking system increases the PV cell out power by about 38% compared with that of a fixed collector.*

Keywords: *Dual axis tracking systems, micro controllers based Mechatronic systems, solar panel efficiency, solar trackers prototypes, solar tracking systems*

I. INTRODUCTION

Nowadays, clean renewable energy sources attract a great attention as an essential mean for solving the energy crisis around the globe. Solar energy is mostly available free of charge all over the world although it is not a continuous energy source. The increasing concern, in the world, about photovoltaic, PV, modules is mainly due to the fact that they convert solar energy directly into electrical energy without pollution, noise and other factors causing adverse changes in the environment. The cost of photovoltaic systems is systematically decreasing as well. They are extensively accepted as one of the renewable electricity resources. They are appropriate for most applications at moderate initial and low maintenance costs.

Applications of photovoltaic systems are classified as stand-alone, grid connected, and hybrid combinations in the form of a cells module or array. These systems are usually combined with batteries for energy storage. Solar tracking systems for maximizing the PV cells efficiency have a motivated great interest in many researches. Photovoltaic generators work most efficiently when the sun is directed perpendicular to their panel surfaces. Although, solar tracking systems significantly increase PV panel's initial and operational costs, the solar collecting system efficiency is reasonably increased in return.

Mechatronic tracking systems ensure the optimal positioning of the PV panels relative to the Sun's position. According to mobility degree classification, there are two basic types of tracking systems namely, mono axis and dual axis systems. The daily motion, tilting motion of the panel axis corresponding to the sun location's latitude angle, is achieved by the mono axis trackers [1, 2]. The dual axis trackers perform both daily and seasonal, tilting and elevation motions, and therefore, they precisely follow the Sun path all over the year. Dual axis tracking systems increase the PV cell efficiency up to 40–45% , than that of an equivalent fixed systems; compared to a lower increase with the mono axis systems of up to 30–35% [3, 4, 14].

Mono axis trackers have only one motion actuator and therefore they are simpler than dual axis trackers. They are of lower initial investment and their control algorithms for tracking the sun's trajectory are easier to be constructed. Although, the dual axis solar trackers can accurately follow the sun trajectory, any time all over the year and anywhere in the world they need two motion actuators and therefore they are complex to be controlled and more expensive [5, 6].

An ideal sun tracker correctly directs the photovoltaic panel to the sun by compensating for changes in the altitude and azimuth angles of the sun [7]. Sun trackers, in most applications, do not exactly follow trajectory motion of the sun. However, it was fortunately reported that sun's trajectory tracking deviation of 10% may cause an energy decrease of only 1.5% [13].

The orientation of the PV strings can be realized, in practice, in two ways, namely, the independent and the simultaneous orientations. In the independent orientation a separate motion actuator is used for each tracking axis. While, with simultaneous orientation the same motion actuator is used for both tracking axis. This is done by using motion transmitting mechanisms

Tracking control issues were approached in several research studies using different techniques, closed loop systems with photo sensors, open loop systems based on astronomical computerized systems, or hybrid combinations [8–11]. Different models, in the literature, for evaluating the sun radiation as an input data were used for designing tracking systems. The root mean square error was utilized as the main comparative analysis element, in constructing a model for estimating the monthly mean solar radiation [15]. Mathematical model for estimating the hourly and daily radiation incident on three-step tracking planes was developed by [12].

In the present work, a dual axis solar tracker was designed and implemented to maximize PV cells power generation from the incident sun energy. Mechatronic principles were used to construct the tracking control system. A commercial arduino UNO R3 micro controller with built in data input/output, servo motors driver, and micro processor modules was used to implement the tracking control software, designed and constructed in this study. Two degrees of freedom, small prototype was designed and constructed in the present work to simulate a PV cells panel tracking system. The prototype was used to check the success of the present tracking control software program. Servomotors actuators, driven by the drivers built in the arduino package and controlled by the present tracking software were used to move the prototype in horizontal and vertical directions. Four LDR light sensors were used to detect the intensity of the solar rays incident at the panel at its, up-right, up-left, down-right, and down-left positions. Experiments were carried out to check the effectiveness of the present solar tracking system. Present experimental results showed that using the present tracking system increases the PV cell out power by about 38% higher than that of a fixed collector.

The present paper is organized as follows. In the following section, section II, the design and construction of the present tracker model has been presented. The tracking control strategy and flow chart of the present study is over viewed in section III. The present experimental work and results are discussed in the section IV. Conclusions of the present study are summarized in the last section. Acknowledgement, references and list of abbreviations are presented at the end of this paper

II. CONSTRUCTION OF THE PRESENT SOLAR TRACKING MODEL

Implementation of a closed loop solar tracker model is presented in this section. The present Control strategy and software flow chart, used to control the present tracking model, are detailed in the next section. Same tracking control procedure can be applied on real much larger solar panels.

A model of a solar tracker was designed and constructed in this work to evaluate the solar tracking control software, developed in this work. It was used to study the effect of solar tracking on the efficiency of PV solar cells panels. The model composed mainly of the mechanical construction and the electronic hardware required for handling signals between the tracking system and the control software. The mechanical and electronic hard ware's components are described in what follows:

2.1 Model mechanical construction

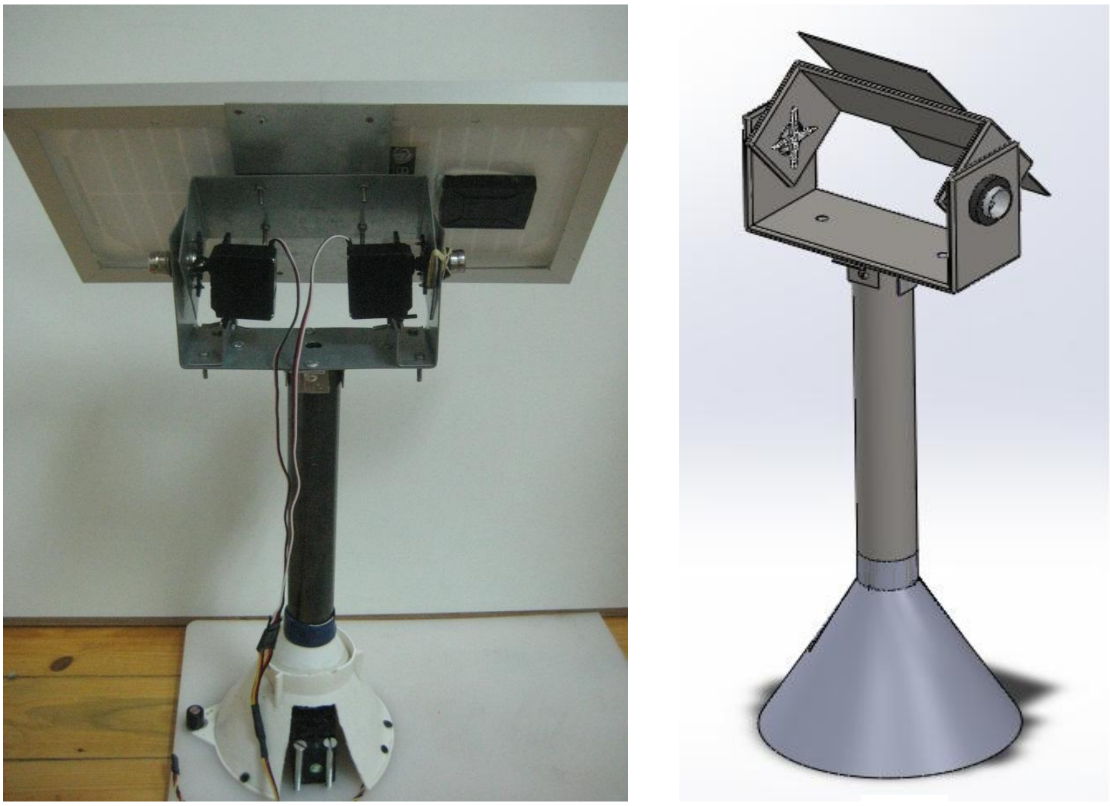
The solar tracker model was designed to have 2 Degrees of freedom motion. This is achieved by utilizing the rotational motion of two groups of servo motors, one to rotate a vertical cylindrical rod, right and left, around z axis, azimuth axis, to follow the sun from east to west directions.

Two U shape brackets, one of them is fixed and the other is movable relative to the fixed one, are mounted by the cylindrical rod. The solar panel is attached to the rotating U bracket to be rotated over the hinges support between the 2 U brackets. The other servo motor, mounted on the fixed bracket, is used to rotate the movable bracket up and down around the x axis, altitude axis, to follow the tracking of the sun in north-south directions.

A conical base, carrying the rod and the brackets, is fixed on a flat plastic base board. The electronic circuits, used for signal handling is fixed on the base board.

Using the solid works 2012 soft ware commercial package, torque analysis was carried out for the rotation of the model around the x axis, with its holding brackets, solar panel and one motor attached, to determine the required size of the x axis rotation servo motor. Another analyses to decide the size of the z axis rotation motor, was performed for the rotation of the vertical rod, holding the whole tracker system, around the z axis. Torque around x axis was found to be equal to 0.34 N.m downward, thus two motors of 0.3 N.m torque capacity, available in the market, both are total of 0.6 N.m, were chosen to do the job. It is therefore, a resultant torque for upward rotation of 0.26 N.m is available, which is enough to rotate the solar cells panel. But for downward rotations the resultant torque becomes 0.94 N.m downward, that is too much and therefore an opposing torque is needed to prevent the solar panel from falling. A suitable rubber seal was used to provide the required friction. Taking into consideration, the weight of the second motor, used, in the analyses didn't alter the calculated torque so much, since the motor is of a small weight, 44 g, relative to the total tracker weight of about 1200 g.

The torque required to overcome the friction forces, corresponding to the whole trucker weight, and to easily rotate the vertical cylindrical rod around *z* axis was found to equal to 2.0 N.m. A motor of a size 2.4 N.m, available in the market was selected to do the job. The final assembled solar tracking model is shown in Fig. 1 below.



(a) **(b)**

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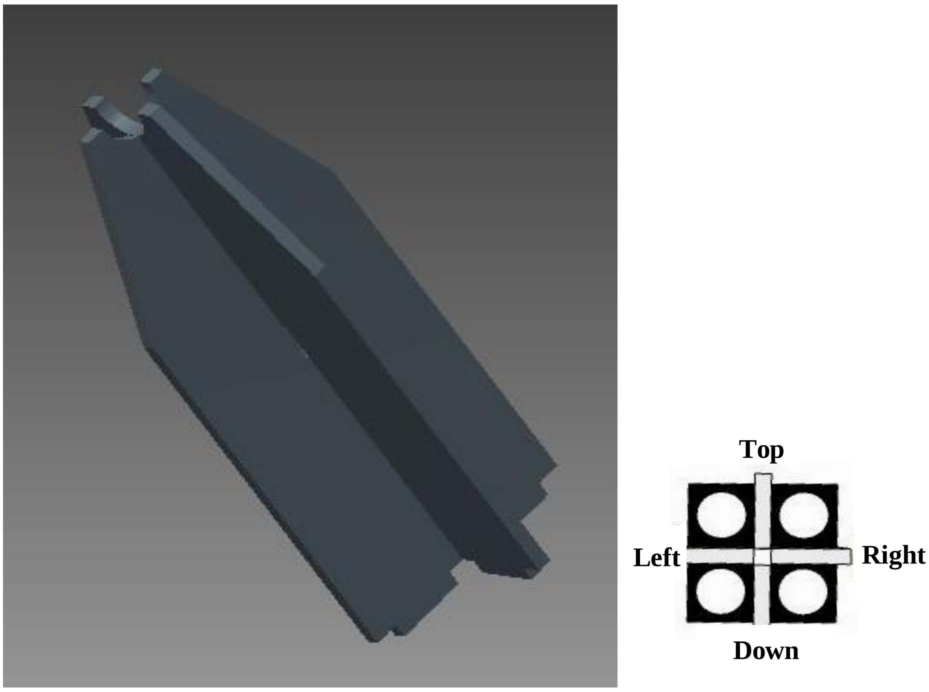
Figure 1 (a) Photographic picture for the tracking model, (b) Final design using the solid works 2012

2.2 Electronic components and circuits

2.2.1. Light intensity detector, LDR

The LDR, light dependant resistance, was selected since it has no polarity, thus easy to interface with circuit, cheap, reliable, and is characterized by high spectral sensitivity, so that variation in light intensity is represented immediately by change in its resistance value. Four LDRs were used to detect light intensity, placed to represent the top-right, top-left, bottom-right and bottom-left directions of the solar panel as shown in Fig. 2 below. A light isolation barrier, 3 mm thick and black colored, shown in Fig. 2, was designed and constructed to prevent sunlight from hitting all the four sensors simultaneously so that the only case when the four sensors receive the same amount of sunlight is when the sun is perfectly normal on the surface of the panel.



(a) (b)

Figure 2 (a) The light isolation barrier, (b) RTDs are isolated by the barrier

2.2.2. Micro controller

Arduino UNO R3 microcontroller was selected in this work. It has two built in servo motor drivers, 8 digital Input/outputs, 6 analog inputs, flash memory of 32 KB and of low power consumption. These specifications are sufficient for the present required tracking task.

2.2.3. Servo motor actuators

As it is detailed above in the mechanical construction section, two motors of type Parallax 900.00005, 0.3 N.m torque and 44 g weight, were selected for the x axis rotational motion, and one motor of type Hitec 805BB+, 2.4 N.m torque is selected to rotate the present tracking system around z axis.

2.2.4. Solar Array

Mono-crystalline solar PV cells were chosen of model RYW-005-012. Although mono-crystalline cells are of less improved performance than the thin film cells, as interpreted from theoretical basis and literature review, they were selected due to their availability in the market. The PV cells were arranged in array assembly as a combination of series and parallel connections to give out put voltage of 5 V of maximum allowable current so that a load of 5 W can be applied. The dimensions of the assembled array are 330 long, 170 wide, and 17 mm thick of total mass with the carrying panel of 0.75 kg.

2.2.5. RTDs signal processing circuit

Voltage divider circuits, as shown in Fig. 3, are used to convert the change in the LDR resistance into analog voltage signal as a control usable signal. The resistance of LDR is theoretically equal to infinity and zero values in fully dark and fully bright conditions respectively. The variable resistance value was experimentally adjusted so that the circuit output voltage becomes near the zero value in the usual surrounding darkness time, 23 mV, and approaching the 5 V value as the light intensity approaches its usual maximum value at the noon time. Voltage divider circuit was repeated four times for the four LDRs used.

The RTDs output analog voltage signal is protected against loading effect, expected in case of utilizing voltage dividers, by using a buffer integrated circuit, IC. Voltage dividers signals are connected to the input of quad unity gain followers OP AMPs integrated circuit so that the OP AMPs output signals becomes loading error free. The RTDs circuit is shown in Fig. 3 below.

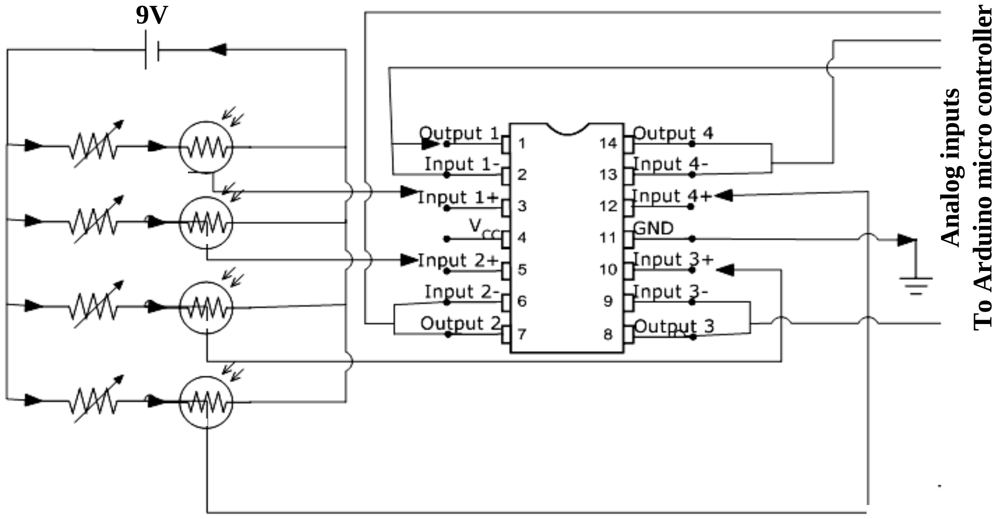


Figure 3 RTDs signal processing circuit

2.2.6. *Arduino micro controller circuit*

The buffered RTDs signals are connected to four analog inputs of the arduino micro controller package. One of the two servo motor driver, built in the arduino package, is used to drive the two motors of the tracker *x* axis rotation, as connecting in parallel. The tracker *z* axis rotation motor is driven by the other arduino driver. Fig. 4 below shows the arduino signals connection circuit.

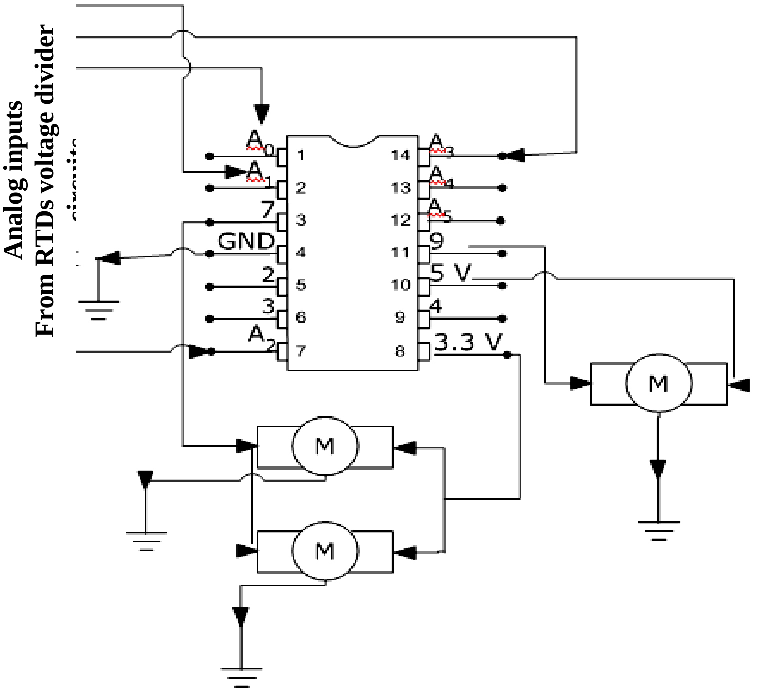


Figure 4 Arduino micro controller signal connections circuit

III. THE PRESENT CONTROL STRATEGY

Light intensity are detected at four panel positions, namely, the top-right, top-left, bottom-right and bottom-left positions. Four LDRs were used to do the job. A light isolation barrier is used to prevent sunlight from hitting all of the four sensors simultaneously so that the only case when the four sensors receive the same amount of sunlight is when the sun is perfectly perpendicular to the surface of the panel. The RTDs signals are sent to the tracking software to redirect the panel normal to the incident sun rays according to how the sun rays hit the panel. Proper control actions are decided and sent to the servomotor drivers so that the change of the sun location is compensated for. The input/output data module of the arduino micro controller is used to exchange the control signals between the tracking control software and the tracking system. The tracking software is processed by the arduino micro processor and stored by its cash memory.

For example, if the top right and bottom right LDR's are receiving sunlight while the other two LDR's are in the shadow, then motor will move the panel to right until all the four sensors are receiving the same amount of the sunlight. Fig. 5 shows a schematic diagram for the tracking control soft ware.

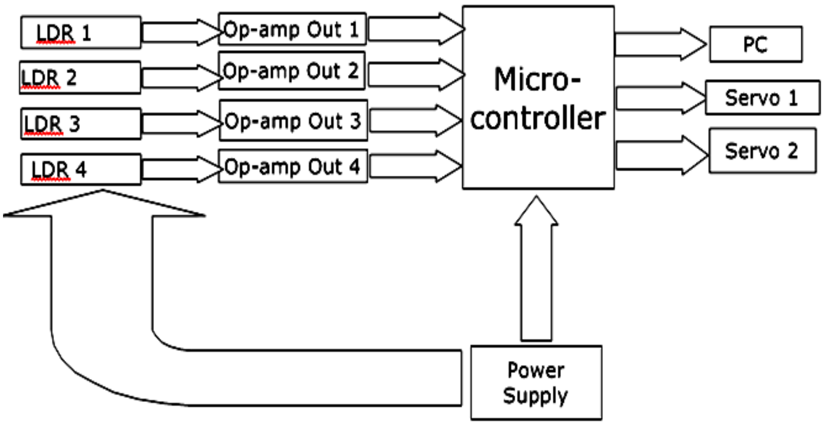


Figure 5 Schematic block diagram for the present tracking software

The RTDs signal pass through the OP AMP buffering circuits on their way to the analog input terminals of the arduino micro-controller. The tracking software, stored in the cash memory of the arduino, reads the light intensity signals. The control strategy of the software is processed by the arduino micro processor. Decided control actions commands, such that rotate with a specified angle increment or not, go to the servo motor actuators through the drivers, built in the arduino circuit. Connection with a personal computer is used to construct the control program and to load it in the arduino's memory.

3.1 The present Control software flow chart

Defining the following terms as:

θ: Rotational angle around x axis
UR: For the up-right sensor reading.
DR: For the down-right sensor reading.
U: For UR + UL
R: For UR + DR
UD: UD = absolute (U – D).

ϕ: Rotational angle around z axis
UL: For the up-left sensor reading.
DL: For the down-left sensor reading.
D: For DR + DL.
L: For UL + DL.
RL: RL = absolute (R – L).

The control target is to achieve both UD and RL equal to zero. But since noise is most probably affects the voltage readings so a dead band threshold is taken as 122 mV, equivalent to a binary corresponding value of 100. So if UD is greater than 100, digital, then if U > D, move the tracker to up, in counter clock wise, CCW, direction, and if D > U, move the tracker to down, in clock wise, CW, direction. Also, if RL is greater than 100, digital, then if R > L, move the tracker to right, in CW direction, and if L > R, move the tracker to left, in CCW direction. The flow chart of the soft ware is shown in Fig. 6.

IV. PRESENT EXPERIMENTAL RESULT

An experimental work was carried out in this study to evaluate the effectiveness of the present solar tracking model. The experiments were performed as follows:

4.1. Testing the control hard ware equipment

Basic control circuits were carried out to test the Arduino microcontroller using a number of buzzers and LED's in order to ensure that the microcontroller is operating as it should be.

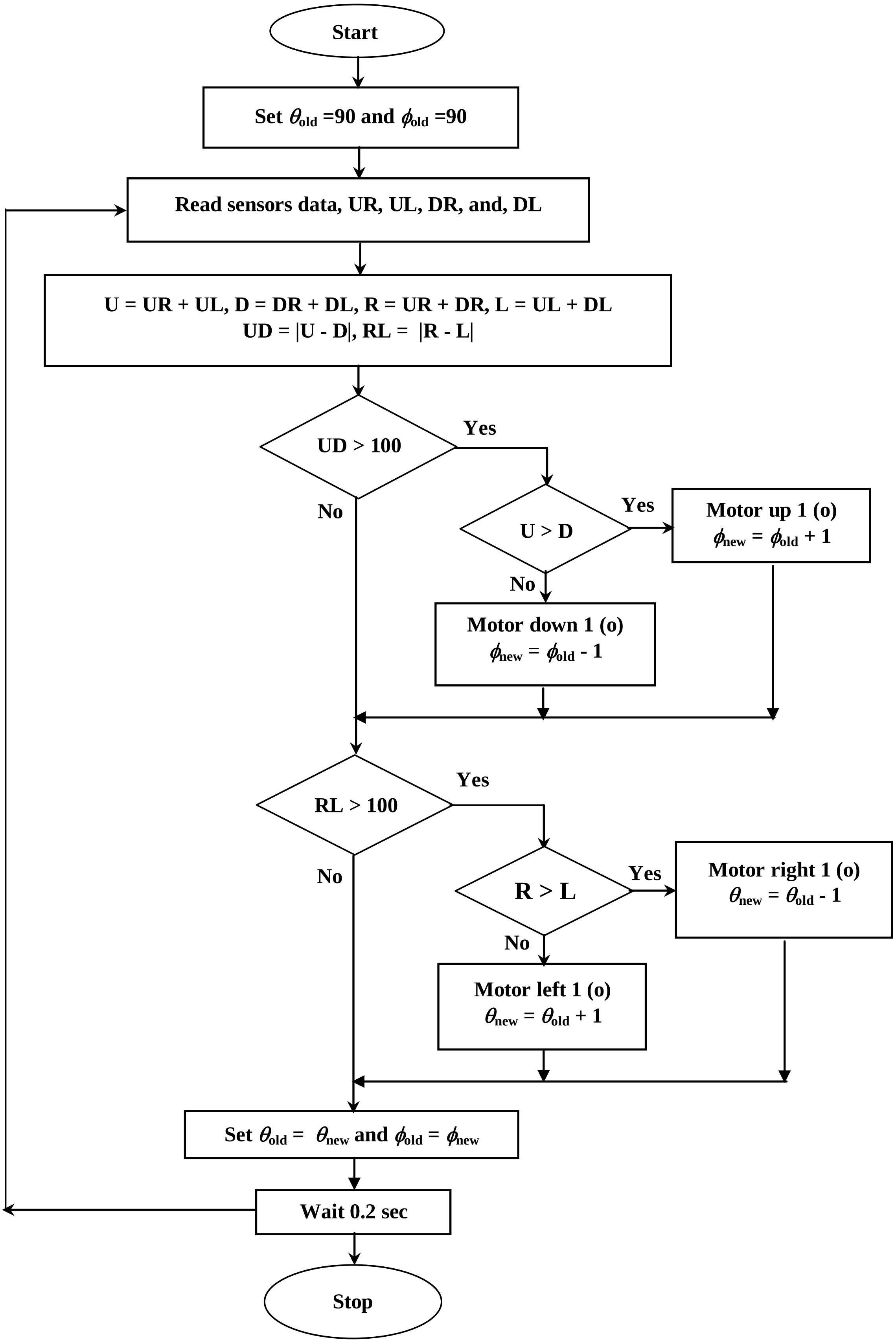


Figure 6 Flow chart of the present tracking control software

Commands for servo motors were written by the arduino software to ensure they are functioning properly under no load conditions. Servos motors are built in feedback controlled to reach a certain specified angle. They are initially set at 90 degrees. A command for increasing the motor angle above 90 (o) cause it to rotate in CCW direction and vice verse. The function "*write (angle value)"* gives a command to the servo motor to rotate to the given angle value, even it is large or less than its current angle. Testing the servos was crucial to ensure the absence of mechanical problems under no load conditions.

4.2. Light tracking experiment

The purpose of this experiment is to ensure that the tracker is functioning properly, attaching the PV cells on the tracker is not necessary in this step as the experiment was conducted in a room with low light intensity, dark conditions, to ensure reaching the light source the LDRs.

Controlling light sources that reaching LDRs is important to ensure that any output is due to light source acting as the sun in this simulation. In this case a torch was used to monitor the movements of the tracker corresponding to light variations.

Torch light was focused on the solar panel, on which the sensors are fixed, from various angles. Test results showed that the tracker successfully moves towards the direction of the torch light wherever it comes from.

4.3. PV voltage generation experiment

The experiment was conducted on two different days. First day, 5 readings were taken every one hour from 11:00 AM to 3:00 PM, representing the most effective daily sun power period. Solar PV cells panel was placed on the tracker, fixed without operating the tracking control system. Solar panel was fixed in the position recommended by the literature under the sun with no tracking occurred.

Second day, another 5 readings were taken at the same times as the previous day, but the tracking control was fully operated. Readings were taken for the panel output generated voltage measured by a voltmeter. The voltage reading is presented in Table 1 below. Experiment was conducted on the 11th and 12th of June 2014. Fig. 7 shows the distribution of the generated voltage for both the tracked and the un-tracked sun power collectors. Experiment data is presented in table 1.

Fig. 7 shows that, the voltage value produced at the noon time, 12 PM, is almost the same for both tracked and un-tracked panels. This result is expected since the fixed panel is already pre directed to be perpendicular to sun light rays at and near the noon time, as recommended by the literature.

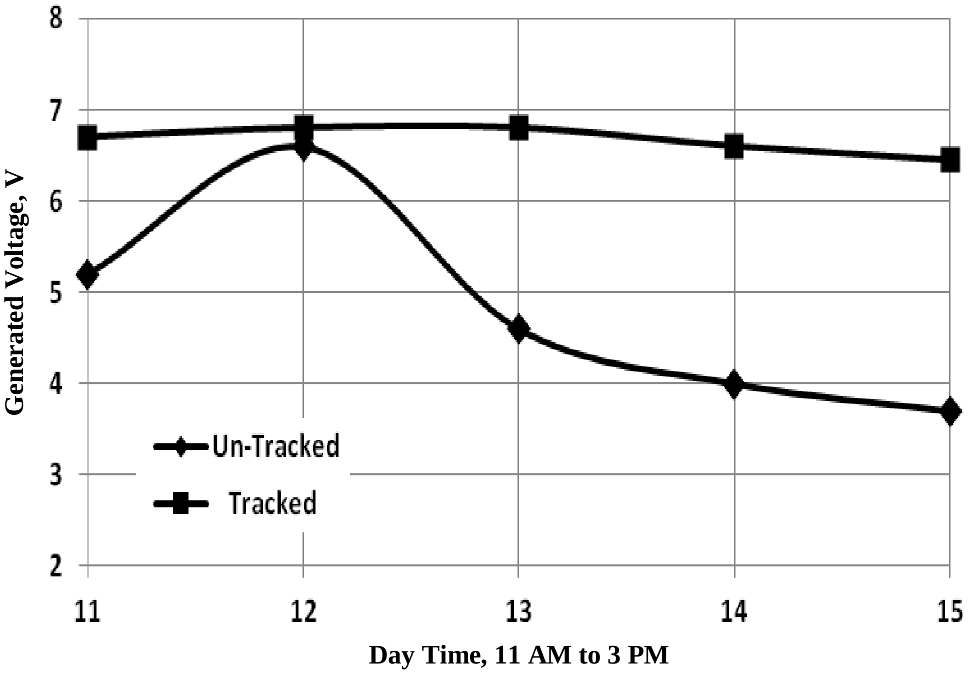


Figure 7 Daily time distribution of the generated voltage data for tracked and un-tracked solar collector systems

Table 1: Readings of the voltage generated experiment

Time	***Generated Voltage, V***	
	Tracked	***Un-Tracked***
11:00 AM	6.70	5.20
12:00 AM	6.80	6.60
1: 00 PM	6.80	4.60
2: 00 PM	6.60	4.00
3: 00 PM	6.45	3.70

Table 1 shows that the average generated voltage values are 6.67 V and 4.82 V for tracked and fixed panels respectively. This result shows that an improvement of 38.4% is gained, in the solar energy collecting efficiency, by using the present solar tracking system.

V. CONCLUSIONS

A dual axis solar control tracking system was designed and constructed in the present work. Two degrees of freedom small prototype was designed and constructed to simulate a tracking system of PV cells panels. A commercial arduino UNO R3 micro controller package was used to execute the present tracking control software. LDR light sensors were used to detect the intensity of the solar light incident on the PV cells panel. The control tracking software receives the light sensors data, according to which, it decides proper actions to actuate servo motor actuators so that change of sun location is compensated for to maximize the PV cells out electric power. Experiments to evaluate the present system tracking performance were carried out to check its light tracking process and the status of its output power along a period from 11 AM to 3 PM, representing the most effective daily sun power period.

Conclusions of the present study are summarized as follows:

1- The present tracking system successfully traced the light source even it is a small torch light, in a dark room, or it is the sun light rays.

2- The present system succeed in keeping the sun incident light rays perpendicular to the surface of the solar cells panel all the day light time.

3- A significant increase in output generated power of about 38% higher than of an equivalent fixed panel is concluded. The output power was measured as the average value of the panel produced voltage over the day light time.

4- The voltage value produced at the noon time, 12 PM, is almost the same for both tracked and un-tracked panels. This result is expected since the fixed panel is already pre directed to be perpendicular to sun light rays at and near the noon time.

ACKNOWLEDGEMENTS

The author would like to express his deep thanks to Mohamed Tarek and Mazen Emad, graduate students of the British University in Egypt, BUE, for their sincere help in constructing the tracker model and in carrying out the experiments.

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Abbreviations

CCW: Counter clock wise.
CW: Clock wise.
IC: Integrated circuit.
LDR: Light dependent resistance.
new: The rotational angle value at the current control step.
old: The rotational angle value at the previous control step.
OP AMP: Operational amplifier.
θ : Tracker horizontal rotational angle around the z axis.
ϕ: Tracker vertical rotational angle around the x axis.
PV: Photovoltaic.