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DESIGN AND CONSTRUCTION OF AN AUTOMATIC SOLAR INSOLATION TRACKING SYSTEM

[1]Gesa, F.N and [2]Kwaha, B.J
[1]Department of Physics, University of Agriculture Makurdi, P.M.B 2373,
Makurdi, Benue State
[2]Department of Physics, University of Jos, P.M.B 2084 Jos, Plateau State
E-mail: [1]gesnewx@yahoo.co.uk, / [2]kwahab68@yahoo.com,

Abstract: In this work, an automatic solar insolation tracking system was designed and constructed primarily for the purpose of optimizing solar energy collection by solar payloads. This was achieved through hardware/software-embedded programme control system. A programmable Microcontroller (PIC16F873A), Light Detection Sensor (CdS NORP12-RS) and a Stepper Motor (Sanyo Denki G-05S) were used. MPLAB IDE compiler for microchip was used to programme the PIC16F873A. The implemented programme enables the PIC16F873A to analyze solar intensities sensed by the CdS NORP12-RS and relays tracking instructions to the stepper motor to produce a torque on payload in the direction favourable to maximum solar intensity. The maximum output voltage of 2.49V was measured from the sensor under bright illumination while the minimum output of 1.83V was obtained under zero illumination. However, the calculated values show a maximum output voltage of 4.90V under bright illumination and a minimum output of 0.84V under zero illumination. The binary resolution corresponding to the higher threshold voltage of 2.49V was determined as 01111111_2 while that for the lower threshold voltage of 1.83V was 01011101_2. The microcontroller uses these threshold values as tracking voltage reference values for the Cadmium-Sulphide (CdS NORP12-RS) photoresistors. The stepper motor with factory stepping angle of 1.8^{o} was half-stepped to 0.9^{o} to produce smaller rotations and precise positioning of payloads. The motor was tested and observed to have yielded a mean stepping angle of 0.825^{o} which was close to the standard value of 1^{o} for an ideal solar tracker. The designed automatic solar tracking system finds application in tracking useful amount of solar energy for solar driers, solar reflectors, solar lenses, and solar modules.

Keywords: Locally Designed Automatic Solar Tracking System.

1.0 Introduction

A solar insolation tracking system is a system that can be used to orient a solar payload towards the sun (Sullivan and Powers, 1993). Therefore, an automatic solar insolation tracker is a system that can be used to orient a solar device towards the sun with less or no human intervention. Even though the harnessing of solar energy from the sun has been successfully achieved, it is not devoid of challenges and limitations. These limitations which include the sun angle movement, weather/climate changes, difficulties in solar collection processes etc.

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have limited the efficiency of solar payloads to a mere efficiency of about 19% (Manikatla, 2005). This implies that an input of 1000W of incident solar insolation would produce just an output of about 190W. The need to increase the efficiency of solar energy collection cannot be over emphasized. Therefore, this research aims at improving the efficiency of solar energy collection process by tracking the position of the sun and aligning the payload at all times in a position of maximum solar insolation.

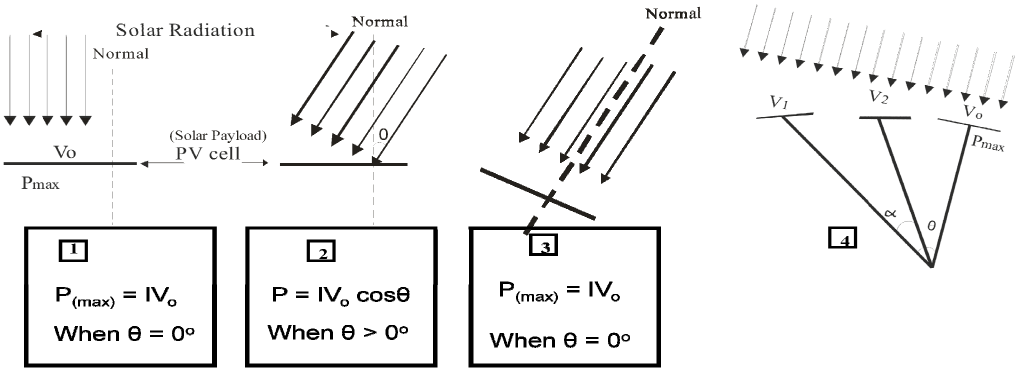

Fig.1 Solar Tracking at a Glance

2.0 Basic Theory and Design Equations

2.1 Light Detection Sensor

Cadmium sulphide (CdS) is a direct band gap semiconductor which has many applications in light detection due to its ruggedness and low voltage requirement. The voltage of the sensor decreases with increased solar intensity while the resistance increases with solar intensity (Mano, 2001).

$$V_{out} = \frac{V_{cc} R_{ref}}{\left(R_{ref} + R_{CdS}\right)} \tag{1}$$

V_{out} is the output voltage, V_{cc} the input voltage, R_{ref} the reference (biasing) resistance and R_{CdS} the sensor's resistance. R_{ref} is given by (Mano, 2001):

$$R_{ref} = \sqrt{R_{1dark} x R_{1bright}} \tag{2}$$

$R_{1\ dark}$ is the dark resistance, $R_{1\ bright}$ the light resistance and R_{ref} the biasing resistor.

2.2 Microcontroller

This contains the microprocessor and other peripherals in a single package. The microcontroller is able to perform a vast range of electronic programmable functions. Its bit resolution is given by (Microchip, 2010):

$$R = 2^n - 1 \tag{3}$$

R is the resolution and n the bit number. Also, (Steyaert et al, 2000):

$$\frac{V_{in}}{V_{out}} = \frac{R_{in}}{R_{out}} \tag{4}$$

where V_{in} is the input signal of the microcontroller, V_{out} the threshold output signal, R_{in} the binary resolution corresponding to the input signal and R_{out} the binary resolution corresponding to the threshold output signal. The switching period, T_{osc} is given by (Steyaert et al, 2000)

$$T_{OSC} = R_T C_T \tag{5}$$

R_T is the timing resistor and C_T is the timing capacitor. The duty cycle D is given as (Condit and Jones, 2004; Austin, 2005):

$$D = \frac{T_{on}}{T_{OSC}} x100\% \tag{6}$$

where t_{on} is the *power on* time and T_{osc} is the switching period. The switching frequency F_{OSC} is (Condit and Jones, 2004; Austin, 2005):

$$F_{OSC} = \frac{1.18}{2\pi R_T C_T} \tag{7}$$

where $R_T C_T$ is the time constant.

2.3 Stepper Motor

A stepper motor is a brushless, synchronous electric motor that can divide a full rotation into a large number of controlled and precise steps. There are typically two types- viz bipolar and unipolar. Austin, (2005) presented the maximum motor voltage V_{max} and motor current I as:

$$V_{\max} = 32\sqrt{L} \tag{8}$$

$$I = \frac{V}{X_L} = \frac{V}{2\pi f L} \tag{9}$$

L is the inductance of the stepping coils, V the voltage in volts and X_L the inductive reactance. The power output P is (Condit and Jones, 2004):

$$P = IV \tag{10}$$

The stepping angle θ and the distance moved per step by the stator D_s can be obtained from (Condit and Jones, 2004; Austin, 2005):

$$\theta = \frac{2\pi}{\kappa n} \tag{11}$$

$$D_s = \frac{2\pi r\theta}{360} \tag{12}$$

where κ is the torque constant and n the number of teeth on the driving wheel of the motor. The torque τ generated is obtained from (Condit and Jones, 2004; Austin, 2005):

$$\tau = P\frac{T_n}{D_S} \tag{13}$$

T_n is the step time interval. The energy dissipation of the motor E_T is given as (Malvino and Bates, 2007).

$$E_T = \frac{1}{2}LI^2 \tag{14}$$

The output impedance Z_o, is given in terms of the resistance of the motor R and the inductive reactance X_L (Theraja and Theraja, 2010):

$$Z_O = \sqrt{R^2 + X_L{}^2} \tag{15}$$

Table 1 Basic Design Parameters of the Automatic solar insolation Tracking System

Parameter	**Value**
Stepper Motor input power	10.2w
Step Motor output Impedance, Z_O	4.1Ω
Motor Torque, τ	61.2Nm
Number of teeth on the Motor stator, n	18
Tracker angular tilt ϕ	24^o
Tracking angle, θ	0.9 per step
Microcontroller Resolution, R	255
Microcontroller switching Frequency, F	4.0MHz
Biasing Resistance R_{ref} for the LDR	10kΩ

3.0 Materials

3.1 Hardware

- Microcontroller Logic Circuitry (PIC16F873A)
- Photo Resistor (Cadmium Sulphide NORP12-RS) interfaced with a Comparator (LM324)
- Stepper Motor (Sanyo Denki G-05S) biased with four bipolar junction transistors.

3.2 Software

- MPLAB IDE 8.0

4.0 Methodology

The procedure involves the following processes:

i. Detecting and determining threshold analog voltage output values of the photoresistor

ii. Interfacing the analog output with the ADC of the microcontroller.

iii. Programming the microcontroller to compare stored digital equivalents of the threshold values, against real time digital values obtained from varying sensor Analog voltage outputs corresponding to various sensor positions.

iv. Driving the stepper motor to step in the direction of highest light intensity.

4.1. Detecting and determining threshold analog voltage output values of the light detecting sensor

The light detecting sensor unit was based on cadmium-sulphide (CDS NORP12-RS). It has a maximum supply voltage rating of 5.0V and dark impedance of 100MΩ. Biasing resistance, R_2 and R_{ref} were calculated using equation (2). $R_{1\ dark} =$ 49700Ω (Measured value under thick black vinyl polythene) and $R_{1\ bright}$= 200Ω (Measured value under intense solar radiation).

$$R_2 = R_{ref} = \sqrt{R_{1dark} x R_{1bright}} = \sqrt{49700x200} = 9940\Omega = 10\text{k (Preferred value)}$$

The output voltage V_{out} of the light sensor as computed from equation (1) is:

$$V_{out} = V_{in}\left(\frac{R_{ref}}{R_{ref} + R_{CdS}}\right) = 5\left(\frac{10K}{10K + R_{CdS}}\right)$$

Four essential values for R_{Cds} were obtained alongside their corresponding V_{out} values (Table 4).

Fig.2 shows the light detection circuit and the comparator (LM 324) which checks the position with the highest solar intensity (position of least resistance). The output triggers the microcontroller via a BC547 transistor to effect a rotation of the stepper motor within 0.01s in favour of such point.

4.2. Interfacing the analog output with the ADC of the microcontroller

The microcontroller chosen for this research converts the analog photocell voltage into digital values and also provides three output channels to control the motor rotation. The PIC16F873A is programmable, cheap, and consumes very little power and space. The pin configuration of the PIC16F873A employed to control the step Motor speed is presented in table 2. Pins not stated were grounded.

When biased with the adequate voltage, the microcontroller receives solar intensities from the three Cadmium-Sulphide resistors through RA_O. The microcontroller compares them via CCP_2 and selects the maximum sensor’s voltage signal as programmed. The controller then commands the stepper motor through pins RB_1, RB_3 and RB_4 to produce the desired rotation of the motor's stator.

Table 2. Pin Configuration of PIC16F873A Microcontroller

Pin Name	Pin No.	Description	Application
MCLR	1	Reset Input	Clears the Memory when in sleep mode
V_{DD}	20	Positive Supply (+5V)	Power Supply to Chip
Vss	8,19	Ground Reference	Ground Reference
OSC_1	9	For Oscillator	Connected to oscillator 4MHz with 10pF
OSC_2	10	For oscillator	oscillator 4MHz with 10pF
RA_0	2	Input/Output Pin	Input of V_{out} from LM324 as speed counter
RB_3	24	Input/Output Pin	Output to control CW/CCW of the motor
RB_4	25	Input/Output Pin	Output to control CW/CCW of the motor
RB_1	22	Control pin	control the phases of the stepper motor
CCP_2	4	Capture/Compare/PMW	Output of Duty Cycle to control motor speed

The resolution and threshold values of the 8-bit microcontroller PIC16F873A are computed using equations (3) and (4).

i. Resolutions

$$R_{in} = 2^n - 1 = 2^8 - 1 = 255_{10} = 11111111_2$$

ii. Threshold voltages

From the resolution above, a 5.0V analog input would correspond to 11111111_2

Therefore the binary resolution corresponding to the higher threshold voltage (2.49V) is determined using equation (4).

$$\frac{V_{in}}{V_{out}} = \frac{R_{in}}{R_{out}} = \frac{5.00}{2.49} = \frac{255}{R_{out}}, R_{out} \approx 127_{10} = 01111111_2$$

Similarly, the binary resolution corresponding to the lower threshold voltage (1.83V) is:

$$\frac{V_{in}}{V_{out}} = \frac{R_{in}}{R_{out}} = \frac{5.00}{1.83} = \frac{255}{R_{out}}, R_{out} \approx 93_{10} = 01011101_2$$

The program written in MPLAB uses these threshold values as tracking voltage reference values of the Cadmium-Sulphide (CdS NORP12-RS) photoresistors.

The Microcontroller used has a PWM switching Period T_{OSC} given by equation (5) for R_T =5kΩ, C_T = 10pF and T_{on} = 200ns (Microchip Data sheet, 2010) as:

$T_{OSC} = 2\pi R_T C_T = 2x3.142x5000 \text{ x } (10x10^{-12}) = 3.142 \text{ x}10^{-7} = 314.2 \text{ ns}$

The duty cycle from equation (6) is therefore:

$$D = \frac{T_{on}}{T_{OSC}} x100\% = \frac{200\eta s}{314.2\eta s} x100\% = 63.7\%$$

The switching frequency of the oscillator is given by equation (7) as:

$$f_{OSC} = \frac{1.18}{T_{OSC}} = \frac{1.18}{314.2nS} = 3755569.7KHz = 3.8MHz \text{ (Preferred value = 4MHz).}$$

4.3. Software Programming of the Microcontroller

The algorithm written in an assembly language was compiled into Solar Tracking program written in machine language (MPLAB 8.0) and coded into the PIC16F873A which is an essential part of this research.

4.4. Driving the Stepper Motor

A unipolar stepper motor was chosen to position the payload because of its precision in positioning, relatively low power consumption and cost-effective number of circuit components. Using equation (8), the maximum voltage rating of the motor coil can be calculated for L= 0.025mH as:

$$V_{\max} = 32\sqrt{L} = 32\sqrt{0.025} = 5.1V$$

From equation (9) the current rating of the stepper motor is obtained thus:

$$I = \frac{V}{X_L} = \frac{V}{2\pi fL} = \frac{5.1}{2x3.142x50x1x10^{-3}} = \frac{5.1}{3.142} = 1.6A \approx 2A$$

Since the motor has two phases, it implies that each phase needs at most 1.0 A to produce the desired torque. However, if the motor is half-stepped, it would need just 1.0A only. With this, the minimum power consumption of the motor can be calculated from the equation (10):

$$P_{\min} = IV = (1A)(5.1V) = 5.1W$$

Using equation (11), we can calculate the number of teeth n, for θ = 0.9 and κ = 0.4

$$n = \frac{2\pi}{\kappa\theta} = \frac{2\pi}{0.4x0.9} = 17.45 \text{ teeth (n= 18, p referred value)}$$

Since the solar angle rotates through 1^o every four minutes, a step interval of 4 minutes is desired.

Using equations (12) and (13), for T_n = 240s the motor torque Motor torque, τ is:

$$D_s = \frac{2\pi r\theta}{360} = \frac{2x3.142x(25/2)x0.9}{360} = 0.2cm$$

$$\tau = \frac{P}{v} = P\frac{T_n}{D_S} = \frac{(5.1)(240)}{0.2} = 6120Ncm = 61.2Nm$$

This torque is suitable for maximum power point tracking of small payloads like Photovoltaic modules and solar collectors placed at a normal distance to the rotor of the motor.

The energy dissipation of the motor is obtained from equation (14):

$$E_T = \frac{1}{2}LI^2 = \frac{1}{2}x10^{-3}x2^2 = 2.0x10^{-3}J$$

The energy dissipation is therefore negligible.

The ohmic resistance and impedance of the motor as given by Ohm's law and equation (15) predicts whether or not the motor will load the succeeding stages.

$$R = \frac{V}{I} = \frac{5.1}{2} = 2.55\Omega \qquad \text{and} \qquad Z_O = \sqrt{R^2 + X_L{}^2} = \sqrt{2.55^2 + 3.142^2} = 4.1\Omega$$

5.0 Tests Carried out

5.1 Sensory Unit test

The measurements of the sensor parameters at different luminance using the light detecting resistor (Cds NORP-12 RS) was carried out and the results presented in Tables 3 and 4.

Table 3. Measurement of Light Sensor Resistance (R_{cds}) for Different Luminance conditions

S/No	Luminance condition(Lux)	R_{cds} (kΩ)
	Total darkness	49.70
2	Cloud-laden light intensity	4.35
3	Average light intensity	2.20
4	Bright light intensity	0.20

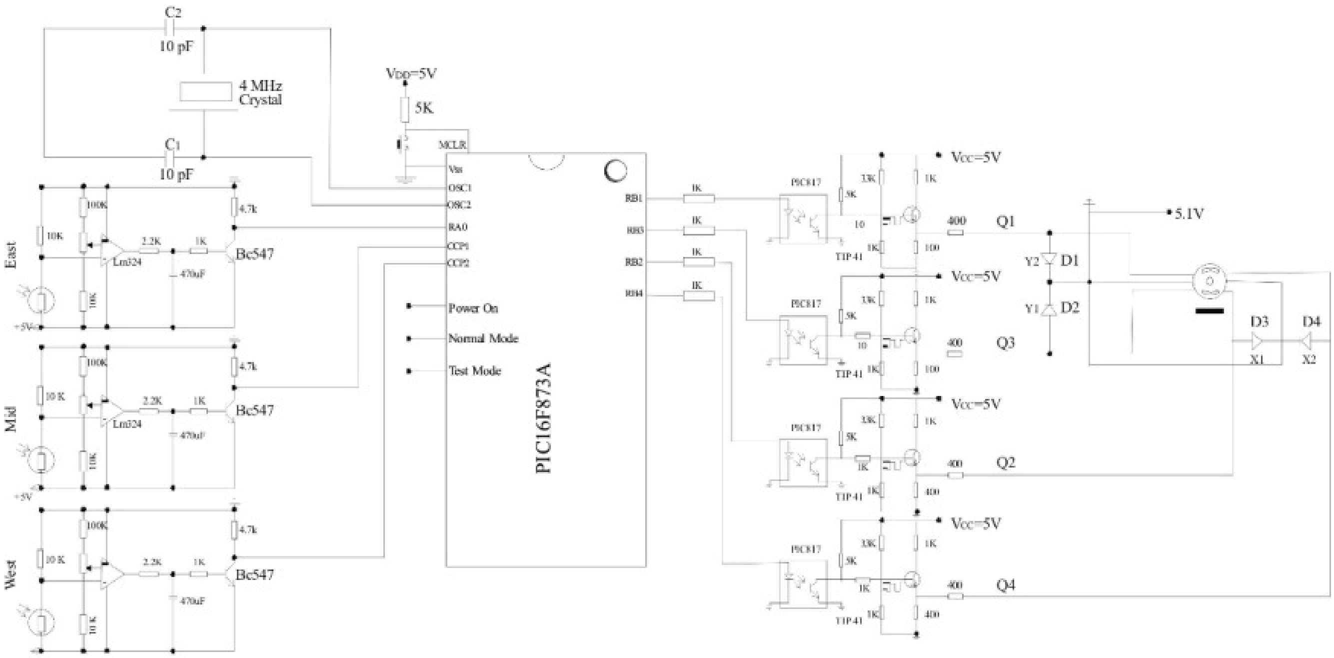

Fig. 2 Circuit for the Implemented Automatic Solar Insolation Tracking System

Table 4. Measurement and Calculation of Light Sensor Voltage Outputs, V_{out} for Different Resistance, R_{cds} of the Sensor

S/No	Luminance Condition (Lux)	(R_{cds}) (kΩ)	V_{out} (V) (Measured value)	V_{out} (V) (Calculated values)	Deviation (V)
1	Total darkness intensity	49.70	1.83	0.84	+0.99
2	Cloud-laden light intensity	4.35	2.10	3.48	-1.38
3	Average light intensity	2.20	2.35	4.10	-1.75
4	Bright light intensity	0.20	2.49	4.90	-2.41

The calculated value of the output voltage is obtained using equation (1): $V_{Out} = \dfrac{V_{cc} R_{ref}}{(R_{cds} + R_{ref})}$

where V_{CC}=5V, R_{ref}=10kΩ (obtained using equation 2 with R_{1dark} = 4970Ω and $R_{1bright}$ = 200Ω).

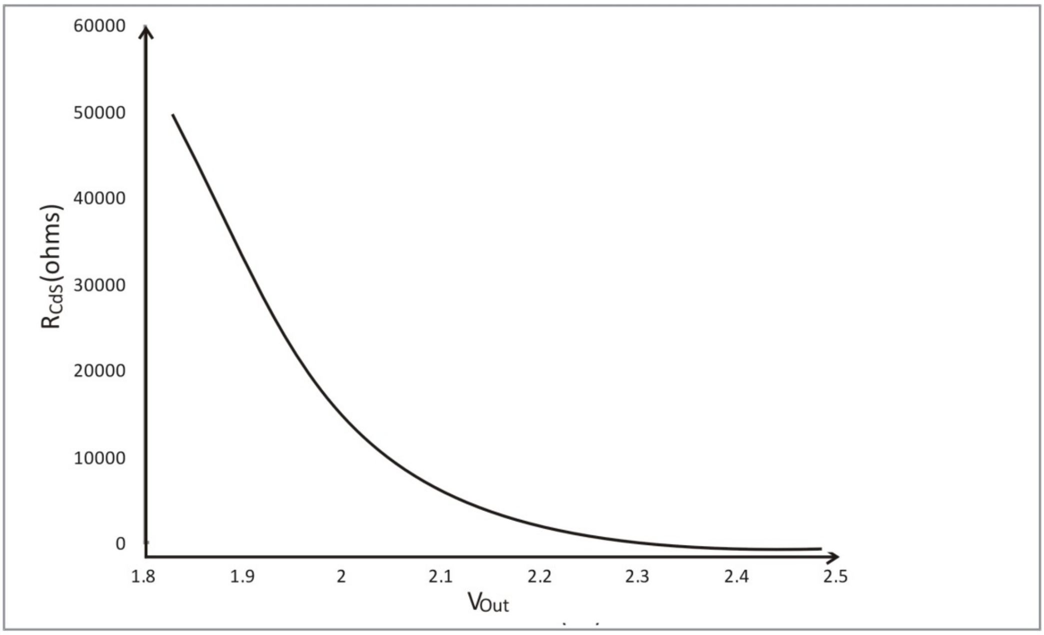

Fig. 3 Graph of Light Sensor Voltage Output, V_{out} (Measured) for Different Resistance, R_{cds} of the Sensor

5.2 Controller/Comparator Circuit Test

Measurement of controller's/comparator's digital outputs was done using analogue-to-digital Multimeter. The result is presented on Table 5.

Table 5. Compared Digital Output/Input of the Controller

Comparator/CCP			
	East Sensor 1	Middle Sensor 2	West Sensor 3
Output	1	0	0
Output	0	1	0
Output	0	0	1
Output	0	0	0

Stepper Motor test

The measurement of the Stepping Sequence of the Motor Circuitry was carried out. The stepping angle was obtained by counting the number of teeth n' turned through by the motor stator in a single stepped movement and then using the equation (1): $\theta = \frac{2\pi}{spr} = \frac{2\pi}{\kappa n}$ to calculate. The result is presented in Table 6.

Table 6. Half-Stepping Sequence of the Implemented Stepper Motor

A	B	RB1	RB3	RB2	RB4	Stepping angle
-	-	0	1	0	1	0.9
-	+	0	1	1	0	0.7
+	+	1	0	1	0	0.9
+	-	1	0	0	1	0.8

$$Mean \quad Stepping \quad Angle \quad achieved = \frac{0.9+0.7+0.9+0.8}{4} = 0.825^{o}$$

6.0 Discussion and Conclusion

An automatic solar insolation tracking system was designed and constructed primarily for the purpose of optimizing solar energy collection by solar payloads. This was achieved through hardware/software-embedded programme control system using a programmable Microcontroller (PIC16F873A), Light Detection Sensor (CdS NORP12-RS) and a Stepper Motor (Sanyo Denki G-05S). MPLAB IDE compiler was used to programme the PIC16F873A. The implemented programme enables the PIC16F873A to analyze solar intensities sensed by the CdS NORP12-RS and relays tracking instructions to the stepper motor to produce a torque on payload in the direction favourable to maximum solar intensity. Tables 3 and 4 present experimental measurements and computations of the resistance of light detecting sensor (C_{dS} NORP12-RS) alongside voltages as its incident luminance intensity changes. The result shows that the resistance of the sensor decreases with intensity; hence the sensor is suitable for design of solar insolation sensory unit. A maximum resistance of 49.7kΩ (with deviation of about 0.01%) was measured from the sensor under total darkness or zero illumination. The minimum resistance obtained under brightest solar intensity was 200Ω (as against the predicted value of 0.0Ω).

Table 4 shows the measured and calculated values of the output voltage, V_{out} from the sensor under varying resistances. The maximum output voltage of 2.49V was measured from the sensor under bright illumination while the minimum output of 1.83V was obtained under zero illumination. However, the calculated values show a maximum output voltage of 4.90V under bright illumination and a minimum output of 0.84V under zero illumination.

The binary resolution corresponding to the higher threshold voltage of 2.49V was determined as 01111111_2 while that for the lower threshold voltage of 1.83V was 01011101_2. The microcontroller uses these threshold values as tracking voltage reference values for the

Cadmium-Sulphide (CdS NORP12-RS) photoresistors. The stepper motor with factory stepping angle of 1.8^o was half-stepped to 0.9^o to produce smaller rotations and precise positioning of payloads. The motor was tested and observed to have yielded a mean stepping angle of 0.825^o which was close to the standard value of 1^o for an ideal solar tracker.

Table 5 shows the comparator's/controller's input and output digital signals for the three comparators coupled to the East, Middle and West sensors respectively. The value of '1' means 'ON' while '0' means 'OFF'. In reality, the outputs of LM324 are analogue in nature. The LM 324 (comparator) gives low or high outputs whenever the negative input voltage is high (2.49V) or low (1.83V) respectively. Since the signals are small, they are difficult to measure. As such, an Analog-to-Digital converter was used to obtain the outputs in binary digits. The null output (0, 0, 0) in Table 5 denote the reset point at dark hour or zero luminance intensity when the resistance of each sensor becomes large and the sensors do not conduct. However, an output like (0, 1, 0) implies that the resistance of the middle sensor is least (its voltage output is highest) compared to the east and west directional sensors. Therefore when this compared signal value is coupled to the microcontroller, it tracks the payload to the central position since that corresponds to the position of maximum photo intensity.

Table 6 shows the drive sequence used in this research. In testing the stepper motor, the drive sequence observes the functionality of the stepper motor. In this work, a half stepping sequence which results in 0.9 degree-per-step is used because it provides greater positioning accuracy. The stepping angle was obtained by counting the number of teeth n turned through by the motor stator in a single rotation and then using the equation (12) to calculate.

The designed automatic solar tracking system finds application in tracking useful amount of solar energy for solar driers, solar reflectors, solar lenses, and solar modules.

Figure 3. Photograph of the Implemented Automatic Solar Insolation Tracking System

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