Arduino Based Sun Positioning for Linear Fresnel Solar Concentrating System with Horizontal Absorber and Varying Width Reflectors

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ABSTRACT

Recently, solar energy is one of key renewable energy resources and is gaining prominence rapidly. Solar energy can be made more viable by maximizing the efficiency of solar thermal systems. Solar tracking can be incorporated into the existing solar systems to yield a realistic solution and to maximize the energy efficiency. The solar thermal system can gain optimal energy during the day when the Sun's rays hit the system perpendicularly, since it receives maximum sunlight. The objective of this paper is to position the solar thermal system with respect to the Sun's movement. In this paper, an embedded system based design is proposed for the one-axis solar-tracking mechanism for the linear Fresnel reflector solar concentrating (LFRSC) system. A geared stepper motor controlled by an Arduino micro-controller is utilized to track the current position of the Sun using sensors. The LFRSC system is connected to the Arduino controller, which positions the solar tracker. The position of the solar tracker is adjusted using the input from two photo-resistors. Due to environmental conditions, sunlight may not fall on both the sensors. Under this circumstance the solar tracker is positioned accurately using the sun positioning algorithm (SPA). The accuracy of the tracking system is verified with the help of a control system. The proposed automatic tracker can be implemented with minimized cost and can yield a reliable structure for LFRSC system.

Keywords: solar energy, LFRSC system, sensors, one-axis tracking, arduino controller, stepper motor, tracking accuracy.

1. INTRODUCTION

Renewable solar energy can be proficiently used uniquely for obtaining concentrated solar power. Commercially accessible concentrated solar power innovations include solar tower, parabolic trough, dish-stirling engine, and linear Fresnel solar system. Among these liner Fresnel solar system is a pervasive technology for solar thermal power systems of larger scale due to its low implementation cost.

Line focusing, linear Fresnel reflector (LFR), utilizes modular and flat mirrors that focusses the Sun's radiation onto the tubular absorber. The absorber through which water flows is long and elevated. Hot water is produced by the focusing sunlight on to the tubular absorber. The heated water is saturated or is heated more to generate steam for utilization in industrial applications or the steam Rankin cycle.

The Earth revolves around the polar axis and its rotation is depicted by the celestial sphere's revolution with respect to the polar axis. The position of the Sun at any given time is specified using hour angle, which is defined as the angle between the meridian that passes through the Sun and that of the site. At solar noon, the value of the hour angle is zero and it increases as we move towards East. A more convenient coordinate

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system can be defined, when the observer is at a location specified by its geographical latitude on the Earth's surface, by a vertical line that overlaps the celestial sphere at two locations namely zenith and nadir. The larger circle that is at right angles with respect to the vertical axis is called as the horizon[1]. A radial line joining the Earth's center and line's projection on the equatorial plane is defined as the latitude of a location. The intersection of the longitude and latitude gives the information about any location on the Earth's surface.

Solar altitude can be defined as the vertical angle between the projection of sun's rays on the horizontal plane and direction of sun's rays passing through the point. The Sun's altitude can also be represented using the zenith angle between the perpendicular line with respect to the horizontal plane and the Sun's rays. Solar azimuth is defined as the horizontal angle computed from south to the horizontal projection of the Sun's rays [2]. Several surveys reported describe the relationship among the parameters utilized for calculating solar positions. In [3], a FORTRAN program is used to determine the parameter required for finding the Sun's position. Following parameters were computed: elevation, time, local azimuth, declination, longitude of the sun, sunrise and sunset in real times. It was stated that the proposed algorithm computes the position of the sun with ± 0.018 tolerance. According to [4], position vector of the Sun with respect to the center of the Earth is depicted in Fig. 1. Here the orthogonal axes from the Earth's center are denoted as CE, CM and CP. These axes points towards the east, meridian and Polaris respectively. A combined vector S to denote the position of the Sun with respect to the center of the Earth can be written as follow:

$$S = \begin{bmatrix} S_M \\ S_E \\ S_P \end{bmatrix} = \begin{bmatrix} \cos\delta\cos\omega \\ -\cos\delta\sin\omega \\ \sin\delta \end{bmatrix}$$

where the hour angle and the declination angle is given by w and d respectively.

In [4], the equations required to focus the solar collector towards the Sun are derived. This is achieved by turning collector about the two perpendicular axes such a way that rays from the Sun are always normal relative to the surface of the collector.
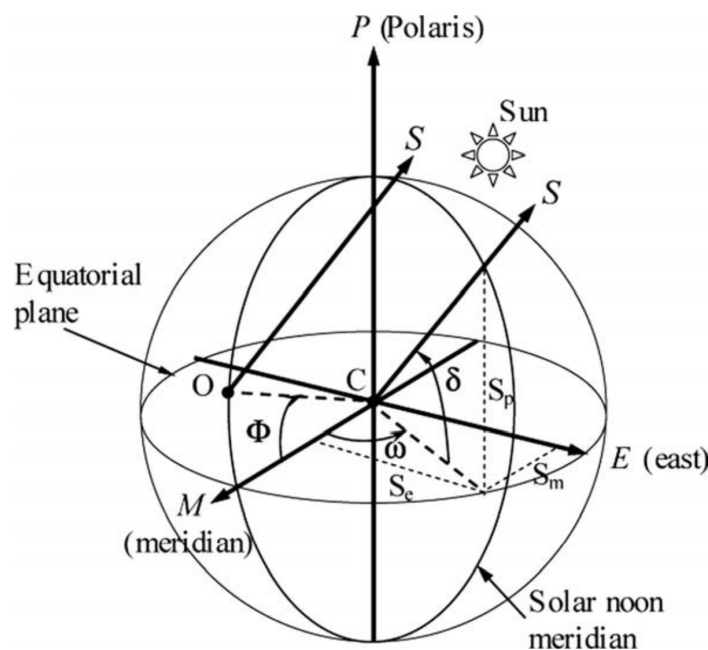

Figure 1: Position vector of the Sun's relative to the Center of the Earth

In [5], a convenient and more efficient sun tracking system is utilized to collect as much solar radiations as possible. The angle of incidence of the Sun rays should be constantly perpendicular so that maximum power output can be ensured from the solar system. However, a consistent tracking of the Sun's daytime movement is required. Thus, in [6], an automatic Sun tracking system is developed which positions system in such a way that it is always focused towards the direct sunlight. In [7], a one axis solar tracking system was implemented and it is stated that two axis tracking system can be used for higher accuracy. Two types of tracking is incorporated for a two-axis sun-tracking system, namely polar or equatorial and azimuth/elevation or altitude–azimuth. Thus, the proposed solar tracker can optimize the collected energy by positioning the PV or photo thermal panels at a position.

The radiation intensity on the solar systems is affected by the diurnal and seasonal changes on the Earth. These movements can be compensated by using a Sun trackers which can orient the system optimally with respect to the Sun. The usage of the Sun tracker is not essential. However, it can be used to boost the energy collected by 10–100% for various time periods and geographical conditions. Due to large energy loss in the driving system, it is not advised to utilize the solar tracker for small scale solar panels. It was discovered that the tracking device consumes more power for 2–3% of the increased energy. In [8], several Sun tracking systems are analyzed and their advantages and disadvantages are discussed. The most effective and commonly used Sun tracking device was found to be in the form of polar-axis and azimuth/elevation types.

The movement of the Linear Fresnel reflector solar concentrating (LFRSC) system is controlled constantly so as to align it towards the Sun's direction. In [9], hybrid hardware cum software solar tracker is designed to offer dependable and reasonable method to align the solar panel with respect to the Sun. Peripheral Interface Controller (PIC) is used to automatically align the solar panels. Two Cadmium Sulfide (CdS) photoresistors are used to sense the light intensity. The CdS photo resistors is a light dependent resistor (LDR) is a light sensitive photocell [9]. The developed software enables the PIC to obtain the sensor data from two CdS or LDR cells (sensor A and sensor B) and their resistances are compared. Two sensors are arranged in such a way, the PIC microcontroller can detect the difference in resistance between the sensors. When one of the sensors is under the shadow region the motor is actuated and the solar panel is moved until both the sensors receive equal amount of light.

Accuracy of the tracking system defines the performance of a LFRSC system. There are many influential factors for Fresnel solar tracking error, such as the structure supporting the reflector, position of the rotation axis position, tracking algorithm, driver accuracy, deviation of geographic latitude-longitude, and related structure error. When north-south orientation and geographic longitude have deviation, the tracking error is biggest at noon, and it is smaller at morning and afternoon on the same day. When the mirror rotating center, solar altitude, and geographic latitude have deviation, the error value changes from positive to negative, and at a certain moment in the midday, the error is zero. Tracking error has a great influence on the solar collection efficiency. For Fresnel solar concentrating system, if the error of tracking is 0.1°, the light energy collected by the receiver tubes decreases by 10%. Therefore, improving efficiency and accuracy of automatic tracking system plays an important role in increasing solar collection efficiency and energy generation and decreasing the cost of solar power [10].

Control system is an integral part of both static and dynamic tracking systems which consists of devices like DC motors, stepper motors, and servo motors to control the direction using either digital or analog control circuit. It is reported that, generally one-axis tracking is sufficient for non-concentrating systems and for systems requiring low to medium level of concentrations [11].

In this paper, an automatic Arduino based tracker is developed for one axis LFRSC system. The main objective of this paper is to position the LFRSC system with respect to the movement of the Sun. Two light dependent resistors (LDR) within an opaque wooden box is placed on both the sides of the reflector frame.

When the reflector frame is normal to the Sun, both the LDRs detect equal amount of light and frame's position is stationary. When light falls on one of the LDRs, the Arduino triggers the geared motor to move in increments of 0.1° until both the sensors detect equal amount of light. Sometimes, due to environmental situations, Sun's light may not fall on both the sensors. In those situations, the Arduino tracker moves the reflector frame according to the elevation angle computed using the Sun positioning algorithm. Thus, the proposed tracking system achieves more tracking accuracy even when the climatic condition is poor or even when the sensor fails.

2. ELEMENTS OF THE TRACKING SYSTEM

The vital elements of any tracking system includes,

- Sun tracking algorithm: To calculate the Sun's azimuth and zenith angles that is utilized for positioning the solar panel or reflector towards the Sun. The tracking algorithm can be based either on mathematical astronomical references or on sensors to detect light intensity in real time.

- Control unit: To implement the Sun tracking algorithm and move the positioning system respect to the Sun.

- Positioning system: To move the solar panel or array of reflectors to focus the Sun at the optimum angles. These positioning systems can either be hydraulic or electrical. Electrical positioning systems employ encoders, linear actuators or variable frequency drives to monitor the current position and to move position determined by the control unit.

- Drive mechanism / transmission: To drive the positioning system which may include linear drives, swivel drives, hydraulic cylinders, worm gears, planetary gears, linear actuators and threaded spindles.

- Sensing devices: To sense the amount of Sun's light for giving input to the control unit. In general, pyranometers are employed to detect the intensity of Sun's light. The efficiency and the power output can be optimized when ambient conditions are used for monitoring humidity, pressure and temperature.

- Limit switches: To control motor speed and to prevent over travels. Mechanical over travel limits can be utilized to prevent the tracker from getting damaged.

- Elevation feedback: To control error. It can be achieved either by using a combination of motor encoder and limit switches or by using an inclinometer.

3. PROPOSED TRACKING SYSTEM

The efficiency of the linear Fresnel reflectors can be improved by capturing maximum radiation and converting it to energy. Solar tracking aid in obtaining increased output depending on the level of tracking accuracy. Tracking systems can be classified as closed loop, open loop and hybrid loop, based on the type of control system utilized. Closed-loop systems employ light sensitive sensors to track the Sun's movement and to position the reflector system dynamically. Closed-loop systems generally yield higher tracking accuracy, however they have the limitations when the feedback signal is lost due to shadow on the sensor or
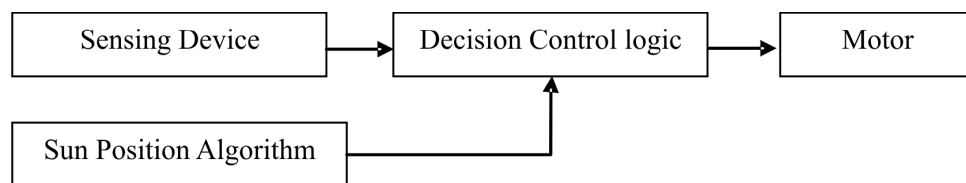

Figure 2: Tracking System Framework

clouds blocking the Sun. In contrast, open-loop architectures calculate solar angles and position the reflector towards the Sun. In the proposed work, a hybrid tracking controller system is developed to regain the maximum advantages from both the systems. Figure 2 demonstrates the proposed tracking system.

3.1. Sensing Device

The tracking system should be implemented with closed loop feedback and the controller has to detect light using a light sensor. A light dependent resistor (LDR) is used to detect the amount of light. The resistance of the LDR is inversely proportional to the amount of light intensity i.e. the resistance of the LDR decreases as the light intensity increases. The LDR comprises of a semiconductor disc with a set of two electrodes on its surface. Figure 3 portrays the CdS photoresistor used in the proposed work. The dark resistance of the mentioned LDR is about 100 kΩ and light resistance is 10 kΩ [12].
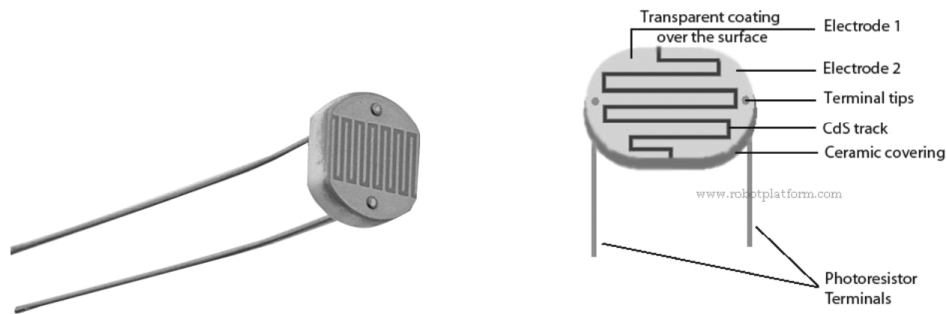

Figure 3: Light Dependent Resistor

Figure 4 portrays the solar sensing device designed for the proposed tracking system that encompass two LDRs or photo resistor enclosed in an opaque box, the unit as a whole acts as a Sun sensor. The Sun sensor is attached to the reflector frame. Figure 5 shows the variation in the LDR resistance (in Ohms) with respect to the illumination from the Sun (in Lux).
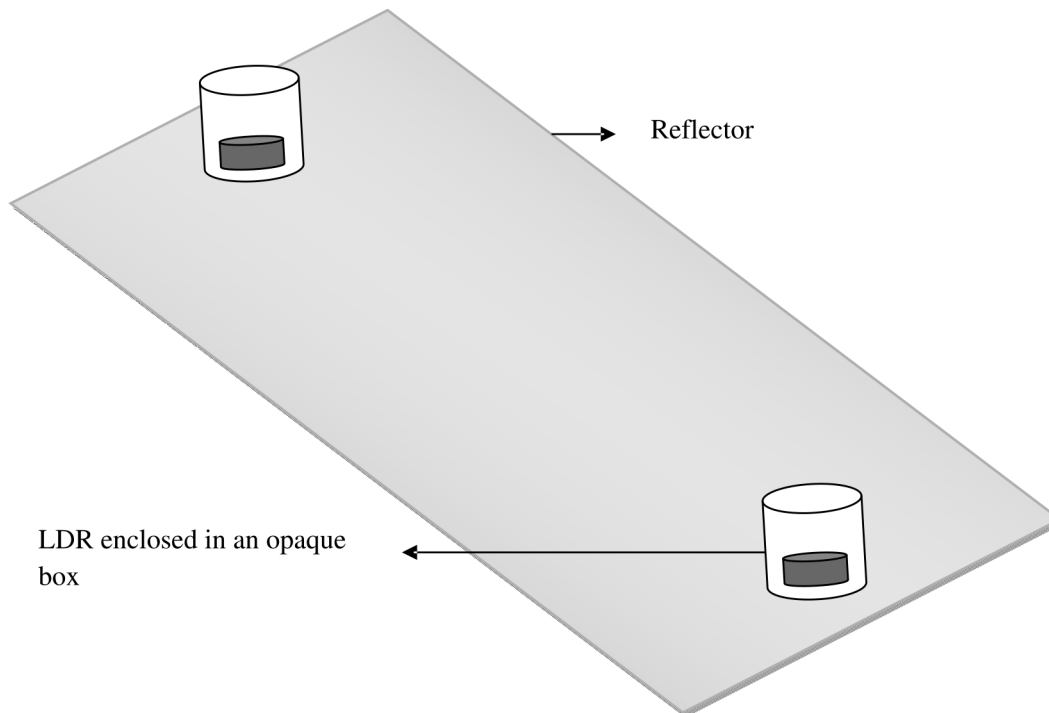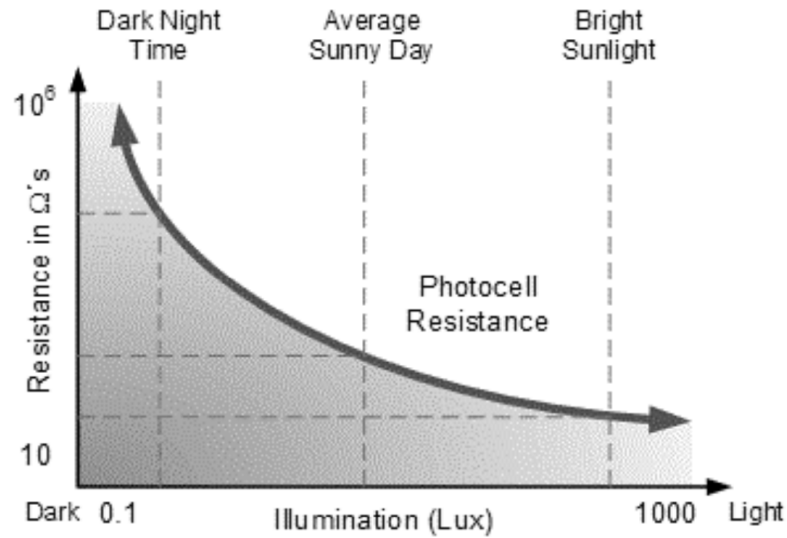

Figure 4: Sensing Device

Figure 5: Light vs. Resistance

3.2. Sun Position Algorithm

Four control elements are to be considered for designing the tracking controllers, they are Sun's position, embedded drive system, control inputs, and control system. The Sun's Azimuth and Elevation angle are used to describe the solar vector or the Sun's position from the global positioning system's perspective or on time and season. The most accurate algorithm to compute the Sun's vector is by the National Renewable Energy Laboratory (NREL) using an astronomical approach[13] and is called as the Solar Position Algorithm (SPA). Accuracy in calculating the Sun's position using the NREL SPA is ~0.0003°. It is also compensates cosmic changes including leap second from 2000 to 6000. The Sun vector is computed as follows.

The detailed NOAA Solar calculator formulas to determine the Sunrise, Sunset, Solar Noon and solar position for any place on Earth are given in this [14].

$$solartime = 720 + 4 * (\zeta - \omega) - E \tag{1}$$

where ω is the hour angle, ζ is the Longitude (in degrees), that refers to the position of the East-West solar collector relative to the Greenwich Meridian Time (GMT), and E is the Equation of time (in minutes)

Hour angle based on solar time, ω is determined as

$$\omega = \begin{cases} \arccos\left(\dfrac{\cos(90.833)}{\phi\delta_s} - \tan(\phi)\tan(\delta_s)\right) \\ 0 \\ -\arccos\left(\dfrac{\cos(90.833)}{\phi\delta_s} - \tan(\phi)\tan(\delta_s)\right) \end{cases} \tag{2}$$

Here ϕ denotes the latitude (in degrees), i.e. the South or North angle of the solar collector with respect to the Equator and δ_s denotes the declination (in degrees) and it is the Sun's angular position at solar noon with respect to the equator, and is determined as

$$\delta_s = 0.00692 - 0.3999\cos\gamma + 0.07026\sin\gamma - 0.00676\cos 2\gamma$$
$$+ 0.00091\sin 2\gamma - 0.0027\cos 3\gamma + 0.0015\sin 3\gamma \tag{3}$$

γ is the fractional year

$$\gamma = \frac{2\pi}{365}\left(day\_of\_year - 1 + \frac{hour - 12}{24}\right) \tag{4}$$

The time equation can be computed using the fractional year as,

$$E = 229.18*(0.000075 + 0.001868\cos\gamma - 0.032077\sin\gamma$$
$$-0.014615\cos2\gamma - 0.040849\sin2\gamma) \tag{5}$$

Thus, the Zenith angle, θ_z (in degrees), can be defined as the incidence angle on a horizontal surface and is obtained as

$$\cos\theta_z = (\cos\phi*\cos\delta_s*\cos\omega) + (\sin\phi + \sin\delta_s) \tag{6}$$

Solar Azimuth (in degrees), the angle of the Sun, clockwise from the north φ can be obtained as

$$\cos(180 - \varphi) = -\frac{\sin\phi\cos\theta_z - \sin\delta_s}{\cos\phi\sin\theta_z} \tag{7}$$

Solar-vector elevation angle from the observer, α_s is given by

$$\alpha_s = 90 - \theta_z \tag{8}$$

3.3. Decision Control Logic

The Sun moves nominally 15° across an arc of sky every hour, i.e., 0.25° for every minute across the arc of the sky. This means that the speed of rotation is not critical [15] & [16]. To achieve high resolution and low power consumption a DC motor with high torque gear transmissions was chosen to rotate the array of reflectors. The microcontroller is programmed to acquire the sensor data for every minute. The flowchart of the control algorithm is shown in Figure 6.

Shadow created by the opaque box surrounding the LDR is the key aspect of the proposed tracking system. The microcontroller is programmed to read the sensor A (LDR1) and sensor B (LDR2). The resistance of the sensor corresponding to the light intensity is inversely proportional i.e. when the light energy is higher the sensor yields reduced resistance value. After reading the resistances of sensors A and B, the microcontroller calculates the difference between the two readings. If the difference is less than a threshold value then there are two possibilities: either both the sensors are under shadow (night time, cloudy day etc.) or both A and B sensors perpendicular to the Sun's position (daytime). During the shadow condition, the microcontroller instructs the motor to position the tracker to the reset position waiting for the Sun to rise from the East. In this case the microcontroller enters into the sleeping mode to save power [17]&[18]. During day time, when both the sensors A and B are facing the Sun, the microcontroller instructs the motor to stop the motion, using fast stop mode in the Hbridge. When the difference is equal to or more than the threshold value then there are two possibilities: either sensor A is under shadow or sensor B is under the shadow. Under this circumstance, the microcontroller tries to keep both the sensors A and B under perpendicular Sunlight. If A is under the shadow, the microcontroller commands the motor to rotate in clockwise (CW) direction and if the sensor B is under the shadow, the motor rotates in the counter clockwise (CCW) direction.

The efficiency of the automated tracking system shown in Figure 6 is limited due to environmental conditions like clouds, fog, rain etc. or any technical problems with the sensors. Due situations like this a large error in tracking will be prevalent. Thus, it affects the amount of concentrated Sunlight towards
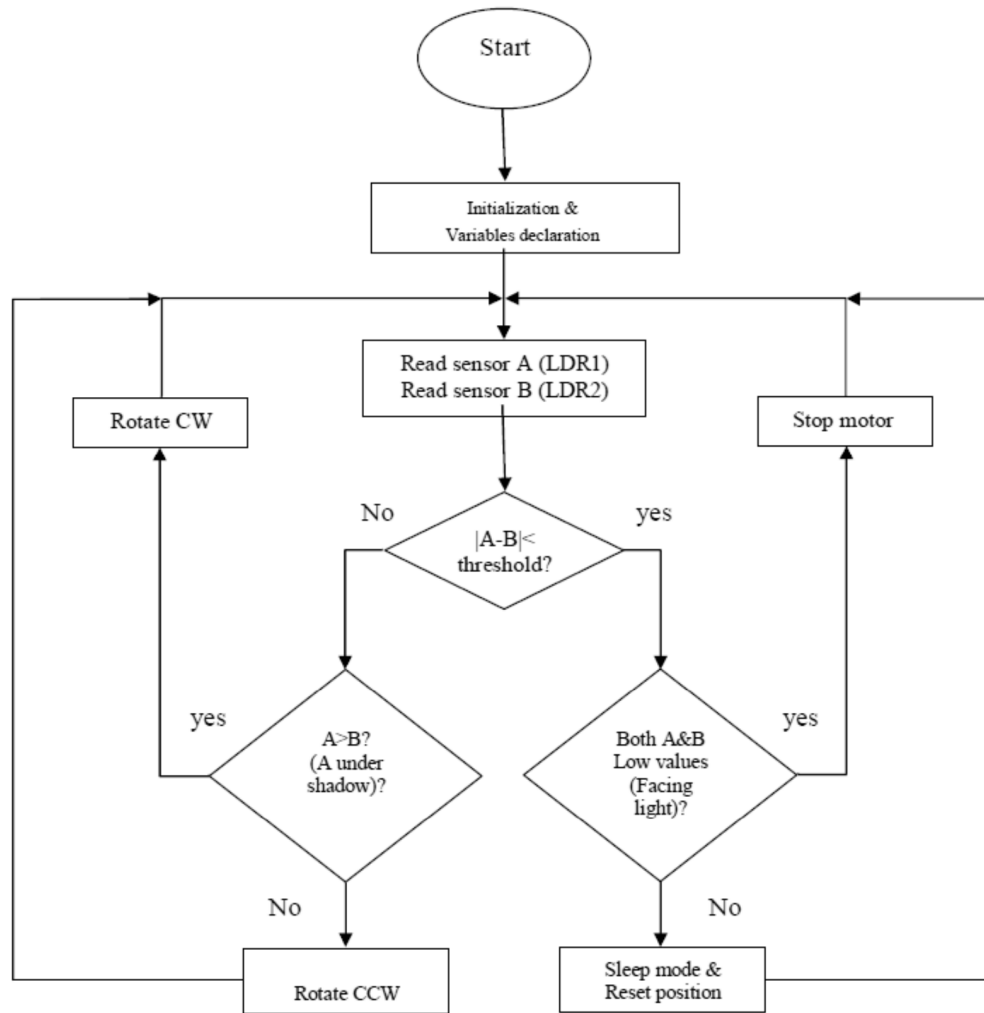
Figure 6: Flowchart of the Tracking System

the focusing element and in turn the concentration ratio and the efficiency of the LFRSC system will be reduced.

In the proposed work the above mentioned limitations are overcome by incorporating the Sun positioning algorithm in the Arduino based decision control logic. When the reflector frame and the absorber is perpendicular to the Sun, two Sun sensors perceive equal amount of light intensity. The decision control logic does not issue signal to activate the motor and the reflector frame is stationary. When the reflector mount is not perpendicular to the Sun, the difference in intensities between the two Sun sensors triggers the Arduino to increment the stepper motor by 0.1° every step until both the sensors are perpendicular to the Sun. The required angle is achieved using gear ratio.

During shadow condition, when both the sensors receive less amount of Sun's light and also the difference between them will be lesser than the threshold. During this scenario, Arduino triggers the automatic mode, where the Azimuth angle of the current position of the Sun is determined using the Sun positioning algorithm and the motor is moved to the computed position from the current location. Thus, the proposed system is more efficient in terms of tracking irrespective of the climatic and sensor conditions.

3.4. Motor

A stepper motor is a brushless DC electric motor where one full rotation is divided into equal number of steps. The microcontroller can be used to control the position of the motor. The size of the motor is carefully

chosen with respect to the given application considering its torque and speed. Electromagnetic coil can be wounded in a two phase stepper motor either by unipolar or bipolar arrangement.

Unipolar motors have two windings per phase. The magnetic pole arrangement can be reversed without changing the direction of current. Bipolar motors have a one winding per phase. The winding current should be reversed so as to reverse the magnetic pole. In general, H-bridge arrangement is used as a driving circuit and its usage is complicated. The static friction effect in the motor can be reduced by dithering the stepper signal at high frequencies.

The windings in the bipolar stepper motor are utilized better when compared to unipolar and hence bipolar is more powerful than unipolar motor of the same weight. Unipolar motor occupies twice the physical space compared to bipolar, however, only half of the windings are used at any given point. Thus, it is 50% efficient. The complications in driving a bipolar stepper motor can be compensated by the availability of abundance of driver chips.

4.   RESULTS AND DISCUSSION

The Arduino Uno lies in the core of the tracking architecture. Figure 7 demonstrates the detailed hardware setup incorporated in the proposed work. Arduino Uno consists of a ATmega328 microcontroller. Its features includes 14 digital I/O pins, 6 analog inputs – each of which provide 10 bits resolution, 16MHz crystal oscillator, USB connector, power jack, 6 among the 14 I/O pins can be used as PWM outputs, 32kB flash memory, 2KB SRAM, 1 KB EEPROM and the operating voltage is 5V.

Two LDR sensors are connected to analog pins A0 and A1. The geared stepper motor is connected to the PWM pins P8 and P9 through L293D. L293D is dual H-bridge motor driver interfacing circuit that takes in a low-current control signal and yields a higher-current signal, which is used to drive the stepper motor.

Punalkulam, TamilNadu, 613 301 is chosen as the test site whose latitude and longitude are 10.66° and 79.05° respectively. The movement of the Sun is observed on the 15th of every month starting from March 2016 to June 2016. Since these months are typical summer in India and are ideal conditions for verifying the efficiency of the proposed system. The polar plot in Figure 8 shows the actual movement of the Sun obtained from [19] over the chosen location. In Table 1, the elevation angle with respect to the Sun's position is observed for the chosen period over the test site are portrayed. The elevation angle of the Sun with respect to the absorber is tabulated for every hour from 6.00 to 17.00 hours on the 15th of every month during March 2016 to June 2016. This table can be utilized as a reference to verify the efficiency of the proposed Arduino tracker. The elevation angles obtained for the same time interval and same duration as the reference case was displayed in Table 2. From the table it can be verified that the proposed tracker yield elevation tolerance with ±0.1° as average tracking error, which can be acceptable and beyond which the efficiency of the solar thermal system is reduced by 10% of its original capability when the focusing is perfect.

5.   CONCLUSION

In the proposed work, an Arduino based tracking mechanism is proposed for LFRSC system to attain maximum efficiency by positioning the reflector frame with an acceptable angle towards the Sun. The proposed tracker comprises of two LDR sensor placed within an opaque box. The Arduino microcontroller lies at the core of the proposed framework. The Arduino controller is used as a decision control logic to detect when the reflector frame should be moved based on unit increment or using the Sun positioning algorithm. The elevation angles obtained using the proposed system is verified against the data obtained for Sun Earth tool. The Arduino proposed tracking system provides a cost effective and accurate solution to the tracking problem.
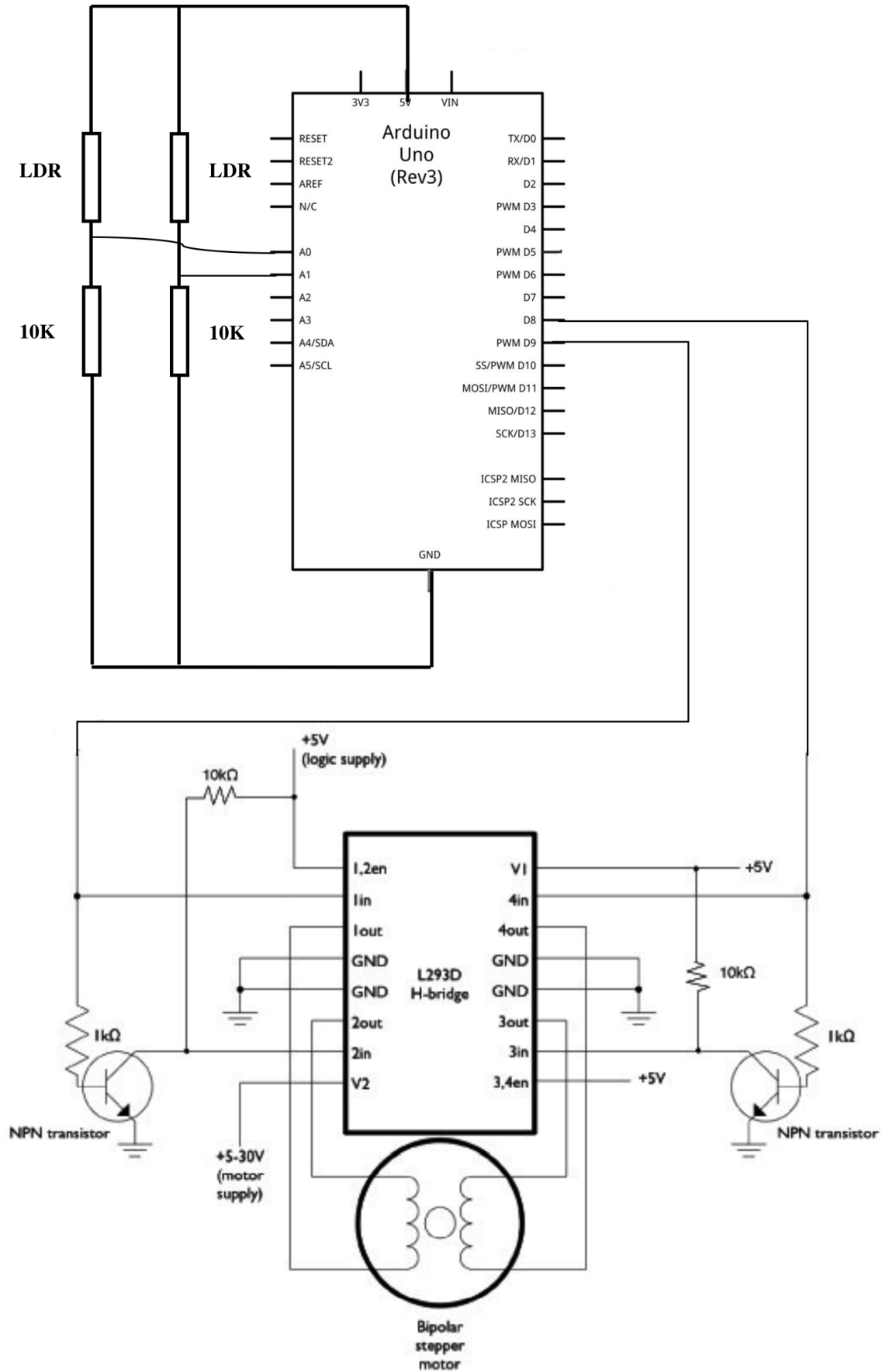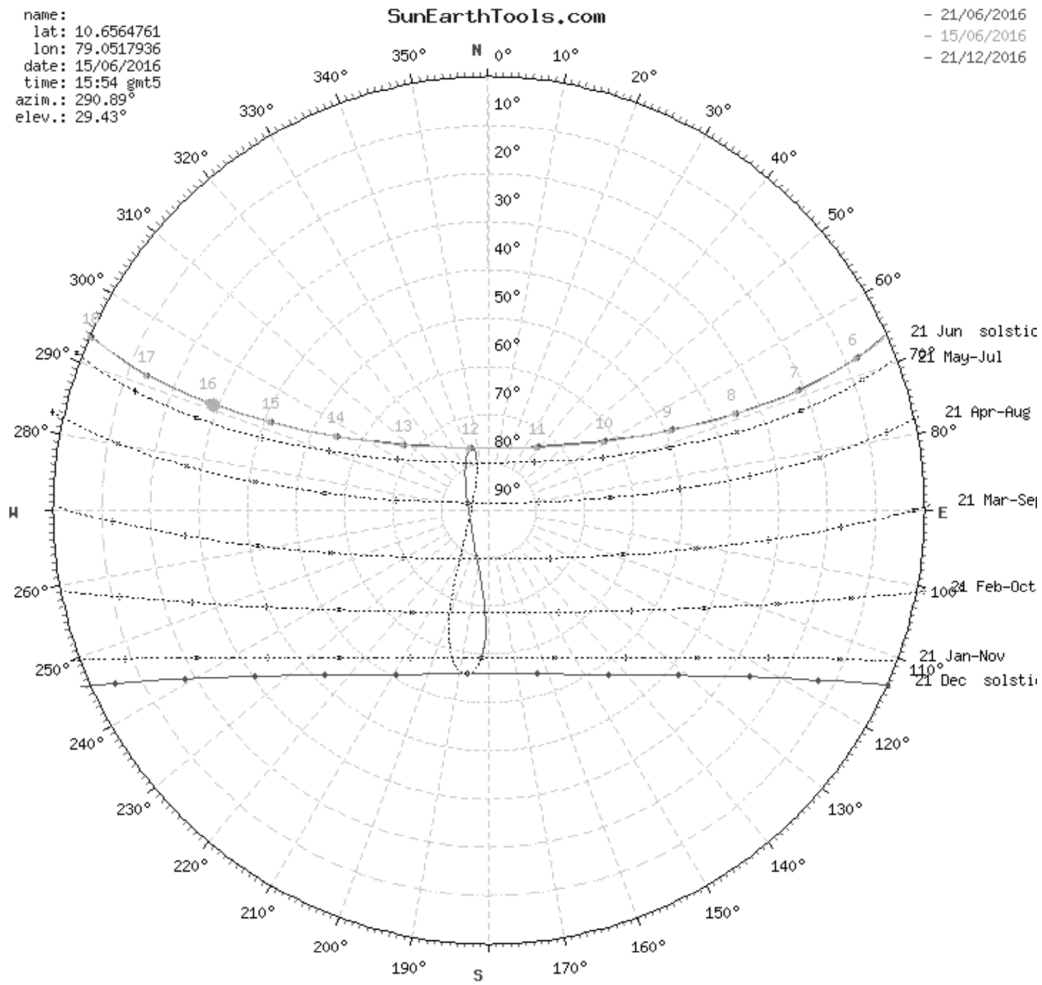
Figure 7: Hardware Connection

Figure 8: Movement of Sun

Table 1
Elevation Angle in degree obtained from sun earth tools

Sl. No.	Time	Mar 15, 2016	Apr 15, 2016	May 15, 2016	Jun 15, 2016
1.	6.00	1.41	5.73	8.07	7.75
2.	7.00	16.12	20.34	22.17	21.46
3.	8.00	30.76	35.01	36.34	35.22
4.	9.00	45.22	49.72	50.50	48.89
5.	10.00	59.26	64.46	64.44	62.09
6.	11.00	71.82	79.20	77.22	73.50
7.	12.00	77.28	85.95	80.39	76.79
8.	13.00	69.05	71.24	69.01	67.96
9.	14.00	55.92	56.50	55.26	55.31
10.	15.00	41.74	41.78	41.15	41.79
11.	16.00	27.22	27.10	26.97	28.05
12.	17.00	12.56	12.46	12.85	14.30

Table 2
Elevation Angle in degree obtained using the proposed framework

Sl. No.	Time	Mar 15, 2016	Apr 15, 2016	May 15, 2016	Jun 15, 2016
1.	6.00	1.5	5.81	8.16	7.83
2.	7.00	16.19	20.43	22.26	21.54
3.	8.00	30.79	35.1	36.42	35.3
4.	9.00	45.31	49.8	50.59	48.97
5.	10.00	59.34	64.55	64.53	62.18
6.	11.00	71.91	79.29	77.31	73.59
7.	12.00	77.38	86.05	80.54	76.94
8.	13.00	69.19	71.42	69.2	68.08
9.	14.00	56.04	56.63	55.44	55.5
10.	15.00	41.84	41.91	41.33	41.89
11.	16.00	27.3	27.18	27.05	28.13
12.	17.00	12.61	12.52	12.91	14.36

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