WRES

2012 - ANTALYA

DESIGN AND IMPLEMENTATION OF A SMART DUAL AXIS SUN TRACKER BASED ON ASTRONOMICAL EQUATIONS

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Abstract

This paper presents a new design algorithm for stand-alone solar tracking system based on ATMEL Microcontroller. The proposed idea of the design is based on astronomical equations to determine the position of the sun in the sky at any time of the day to calculate the tilt angle and polar angle for the two axis tracking purposes. The system is capable of tracking the sun properly at any position on the earth because of the general nature of the algorithm used in the design. At the same time the system reliability, cost effectiveness, precision and flexibility are taken into consideration.

Keywords: Dual axis solar tracker, microcontroller, embedded system.

1. Introduction

The sun is the Earth's nearest star and the source of virtually all the Earth's energy, producing 3.8 × 1023 kW of power in huge nuclear fission reactions. Most of this power is lost in space, but the tiny fraction that does reach the Earth, 1.73 × 1016 kW, is thousands of times more than enough to provide all of humanity's energy needs [1]. The solar cell is a key device that converts the light energy into the electrical energy [2].

The emergence of interest in solar energy utilization has taken place since 1970, principally due to the then rising cost of energy from conventional sources. *Solar radiation* is the world most abundant and permanent energy source. The amount of solar energy received by the surface of the earth per minute is greater than the energy utilization by the entire population in one year. For the time being, solar energy, being available everywhere, is attractive for *stand-alone systems* particularly in the rural parts of developing nations [3].

2. Tracking Systems

The solar incidence angle, θ, is the angle between the sun's rays and the normal on a surface. For a horizontal plane, the incidence angle, θ, and the zenith angle, ϕ, are the same. The angles shown in (Figure 1) are related to the basic angles. For a two-axis tracking mechanism, keeping the surface continuously oriented to face the sun at all times has an angle of incidence, θ, equals to 0°. This, of course, depends on the accuracy of the mechanism. The full tracking configuration collects the maximum possible sunshine. The slope of this surface (β) is equal to the solar zenith angle (Φ), and the surface azimuth angle (Zs) is equal to the solar azimuth angle (z) [4].

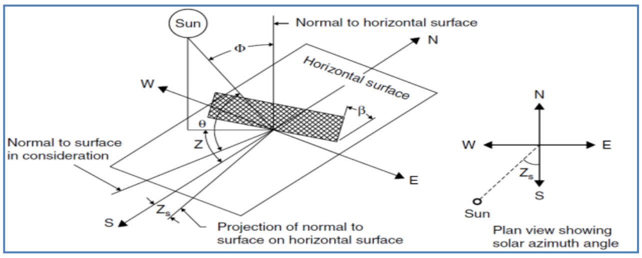

Figure 1. Solar angles diagram

A solar tracker is a device for orienting a solar photovoltaic panel or concentrating solar reflector or lens towards the sun. The sun position in the sky varies both with the seasons (elevation) and time of day as the sun moves across the sky. Solar powered equipment works best when pointed at or near the sun. There are many types of solar trackers of

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varying costs, sophistication, and performance. The required accuracy of the solar tracker depends on the application [5]. Tracking systems are support platforms that orient solar photovoltaic module assemblies by keeping track of the sun's movement, thus maximizing solar energy power generation efficiency. Trackers are classified as passive or active and may be constructed to track in single or dual axis. Trackers are described as being either two-axis trackers, which track the sun both in azimuth and altitude angles so the collectors are always pointing directly at the sun, or single-axis trackers, which track only one angle or the other [6].

3. Solar Angles

3.1. Declination angle, δ

As shown in (Figure 2), the earth axis of rotation (the polar axis) is always inclined at an angle of 23.45° from the ecliptic axis, which is normal to the ecliptic plane. The ecliptic plane is the plane of orbit of the earth around the sun. As the earth rotates around the sun it is as if the polar axis is moving with respect to the sun. The solar declination δ is the angular distance of the sun's rays north (or south) of the equator, north declination designated as positive. As shown in (Figure 3), δ is the angle between the sun-earth center line and the projection of this line on the equatorial plane. For any day of the year δ(n) , in degrees may be determined with good accuracy based on the following seven-term-Fourier expansion [7, 8, 9]:

$$\delta(n) = 57.296[0.006918 - 0.399912\cos(\omega) + 0.070257\sin(\omega) - 0.006758\cos(2\omega) + 0.000907\sin(2\omega) - 0.002697\cos(3\omega) + 0.001480\sin(3\omega)] \quad (1)$$

Where ω is the day angle in radian, ($\omega = 2\pi(n-1)/365$).

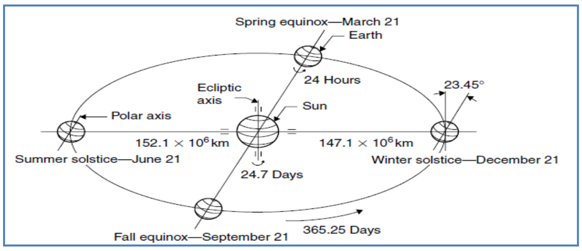


Figure 2. Annual motion of the earth about the sun

3.2. Equation of Time, ET

The apparent solar time varies slightly from the mean time kept by a clock running at a uniform rate. The variation is called the equation of time (ET). The ET arises because the length of a day, that is, the time required by the earth to complete one revolution about its own axis with respect to the sun, is not uniform throughout the year. Over the year, the average length of a day is 24 h; however, the length of a day varies due to the eccentricity of the earth's orbit and the tilt of the earth's axis from the normal plane of its orbit.. The values of ET(n) in minutes as a function of the day of the year (n) may be obtained with good accuracy based on the following five terms of the Fourier expansion [4,8,9]:

$$ET(n)=229.18[0.000075+0.001868\cos(\omega)-0.032077\sin(\omega)-0.014615\cos(2\omega)-0.04089\sin(2\omega)] \quad (2)$$

Where ω is the day angle in radian; $\omega = 2\pi(n-1)/365$.

3.3. Hour angle, h

The hour angle, h, of a point on the earth's surface is defined as the angle through which the earth would turn to bring the meridian of the point directly under the sun. (Figure 3) shows the hour angle of point P as the angle measured on the earth's equatorial plane between the projection of OP and the projection of the sun-earth center to center line. The hour angle at local solar noon is zero, with each 360/24 or 15° of longitude equivalent to 1 h, afternoon hours being designated as positive. Expressed symbolically, the hour angle in degrees is given by [4]:

$$h = \pm 0.25 \text{ (No. of minutes from local solar noon)} \quad (3)$$

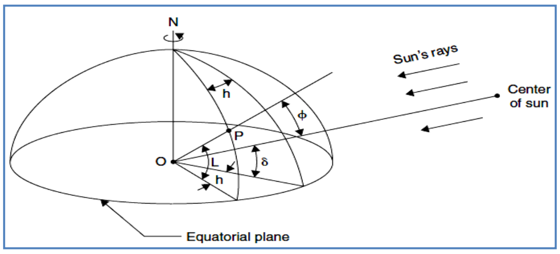


Figure 3. Definition of latitude, hour angle, and solar declination

Since the hour angle at local solar noon is 0°, with each 15° of longitude equivalent to 1 Hour, the sunset and sunrise times, (Hss and Hrs) in hours from local solar noon are given by:

$$\mathbf{Hss = -Hrs = \frac{1}{15}\cos^{-1}(-\tan L\ \tan\delta)} \quad (4)$$

Where L is the latitude in degrees, see (Figure 3). The day length in hours is twice the sunset time, therefore, the length of the day in hours is given by:

$$\text{Day length (DL)} = \frac{2}{15}\cos^{-1}(-\tan L\ \tan\delta) \quad (5)$$

4. Theory of Tracking

On entering the Time, Date and Location latitude the control unit calculates the δ and ET according to the day of year (n). These calculations are made once a day and the Tilt Actuator (TA) position will be based on the first one of them.

TA= 90- abs (L- **δ**) (6)

The second equation for the ET will be used to calculate the Mid Day. Mid Day is local noon

Local noon = 12:00 – (ET (min)/60) (7)

The Sunrise and Sunset times can easily be calculated as follows:

Sunrise time = Mid Day – DL/2 (8)

Sunset time = Mid Day + DL/2 (9)

To find the sun location at any time on its path we need to introduce the Polar Angle (PA) in degrees as:

PA (local time) = 90 - (Local noon -Local Time)/4 (10)

It follows that, the Starting Tracking Angle (STTA) and Stop Tracking Angle (SPTA) in degrees may be defined as:

STTA = Polar Angle(Sunrise + Hold Time) (11)

SPTA = Polar Angle(Sunset - Hold Time) (12)

Where, Hold Time is the chosen time to hold tracking after sunrise or before sunset since the sun irradiance is low at these times.

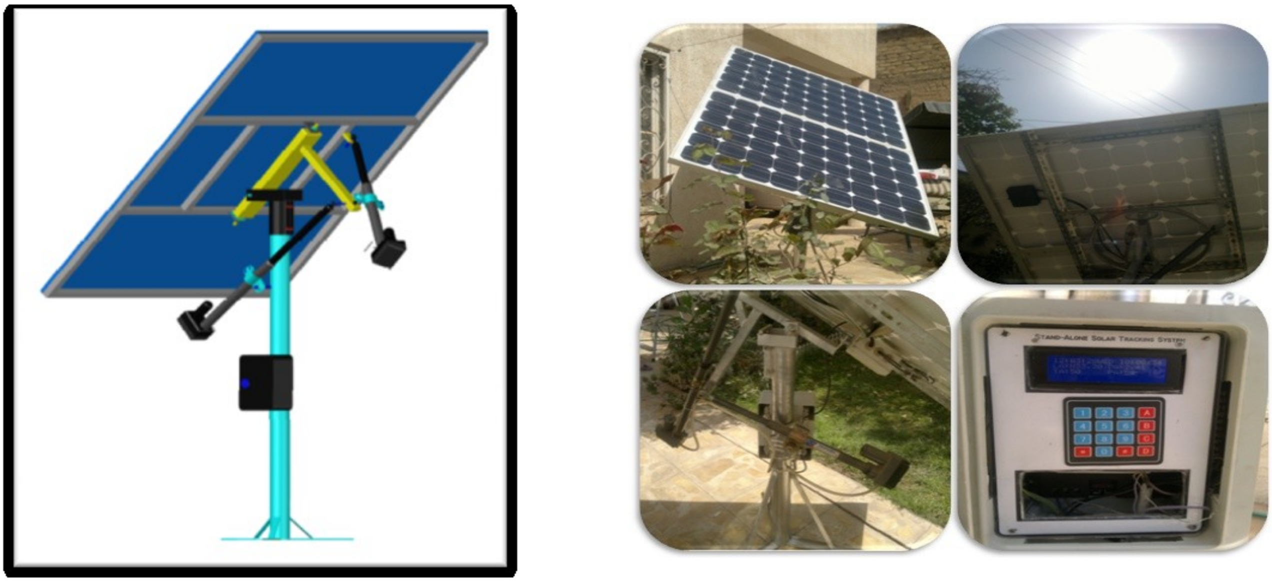
5. System Software

The Microcontroller is programmed by using Flowcode v4 software. At the beginning, the MCU initializes the I^2C Bus to start communication with RTC unit then it asks the user to enter the time, date and location latitude or skip to load these data from the RTC unit. The location latitude is saved in the free memory inside the RTC. After that the MCU unit asks the user to enter the mechanical limitation of the tracker. The user has to enter the minimum tilt angle (TA_{Min}), the maximum tilt angle (TA_{Max}) and the Number of pulses per degree (PPD).

The same calculations will be used for both actuators. At this stage, the MCU has all the required date which can be updated at any time. Because of using the *Reed* sensor which is built inside the actuator, the system needs to reset both motors to zero location. This can be done by resetting both motors through driving them to the zero location and detecting the out pulse. If there is no out pulse from the actuator for specific time the MCU considers the actuator has reached its limit. The system calculates the declination angle, equation of time, sunrise time, sunset time, start tracking angle and stop tracking angle, and then drives the tilt actuator to the calculated angle and the polar angle to the start tracking angle. After these processes, the panel is ready to move for its final position, but the system reads the time periodically. If the local time is less than the start time or greater than the stop time then, the system will stay freeze without doing anything. Else the system will drive the polar actuator to its specified location. The tilt actuator is set in the initialization phase for its specific location. It is also adjusted at any time the tilt angle is increased by one degree. At the same time the system drives the polar actuator one degree every 4 minutes from the starting tracking angle to the stop tracking angle.

6. Mechanical Specifications

The mechanical system is designed to achieve the maximum efficiency. The used actuator should be able to handle the solar panel weight, wind load and able to stay fix after the release of the driving power. The used actuators are 12" & 18" stroke length (12" for the tilt angle actuator and 18" for polar angle actuator), 24VDC, Standard Duty Actuator, Adjustable Limit Switches, Up to 4500N Static, Reed Switch Sensor, 48 pulses per inch. The maximum load on the solar panel includes static and dynamic loads. The static load is the panel weight (2 x 11kg=22kg) with frame weight. The dynamic load is the wind load which can be calculated according to the maximum wind load per square meter in the solar panel location. (Figure 4-a) shows an Auto CAD drawing for the designed tracking system. (Figure 4-b) shows some of the solar tracker photos from different views. It also shows the control box LCD screen and keypad on duty in Baghdad 33^o:30", 2012/03/28, 10:00.



(a) (b)

Figure 4. a) AutoCAD drawing for the designed system, b) Photos for the tracker system

7. System Hardware

Two solar cells with maximum power of 130W each are connected in parallel to supply 24 V/ 2x4.91A to the charge controller. The control unit consists of complementary units as shown in (Figure 5). The power regulator unit is responsible to regulate the input voltage from the solar panel battery. The control unit needs 24 V for the actuators and 5V to drive the relays. The microcontroller (ATmega32) controls the whole system including the real time controller unit, (RTC) which has 32768 Hz crystal for accurate timing. The other important feature of this controller is the available flash RAM inside it which has been used to save the latitude and the last actuator location time. A keypad and LCD are used as input and output devices. Finally, the drive circuit enables the power and drives both actuators in both directions. There are three relays for power management. The first enables and disables the main power, the second switches the polarity to control the rotation of the motor left or right, while the third is responsible for switching the power between actuators. The Reed sensors are driven from the same enable signal to give feedback pulse to MCU. These feedback signals are read by the MCU unit to detect the new actuator position.
The Atmel Microcontroller (ATmega 32) is designed with new features which enables it to deal directly with trigonometric functions. The system utilized these new features to calculate the declination angle, equation of time, day length..etc.

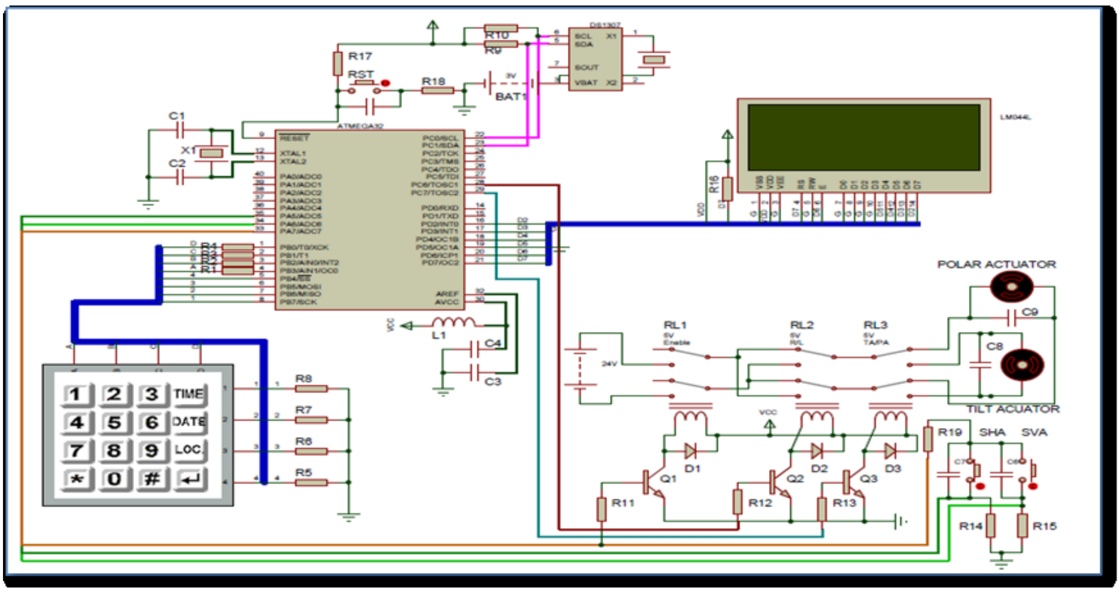


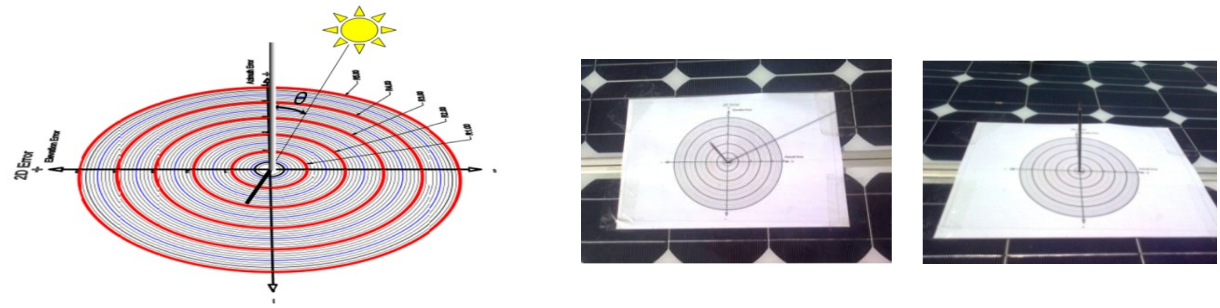
Figure 5. Schematic diagram for the electronic circuit

8. Measurements and Calculations

The adopted algorithm optimizes the tracker efficiency by increasing the solar irradiance to the maximum on facing the sun and reducing the consumed power by the tracker system via the adopted new electrical and mechanical designs. The perfect tracker should keep the solar ray incidence angle, θ approximately equals to 0^o.To measure this angle practically, the system adopts shadow measuring method. This method is based on measuring the shadow length of a rod of specific length fixed perpendicularly on the solar panel. The solar incidence angle, θ is found by using the following equation:

$$\theta = \tan^{-1}\left(\frac{L_S}{L_R}\right) \quad (13)$$

Where L_S and L_R represent the shadow and the rod lengths respectively. (Figure 6-a) shows the adopted practical procedure to measure this angle. Practically, the tracker was turned off at 11:00 on 3rd April 2012 so as to measure the incident angle of the sun's ray. (Figure 6 b) shows the illustration of the shots taken before and after starting the tracking. The shadow length was measured by observing the circular scale that was fixed on the panel. This scale gives the two dimensional display so that the shadow angle represents an indication on the direction the error.



(a) (b)

Figure 6. a) Solar ray incidence angle calculation method b) Photos for the practical set-up

By observing the tracker from [9:00 to 15:00] on 3rd April, and measuring the shadow length to evaluate the system tracking efficiency, Table 1 lists the tracking efficiencies ($= \cos(\theta)\%$) for different times of the day. The overall tracking efficiency over the whole day is the average of these readings and is found to be (99.79%).

Table 1. Tracking Efficiency

Time	Shadow Length (mm)	θ (deg)	Efficiency $\cos(\theta)\%$
09:00	9	5.14	99.60
09:20	8	4.57	99.68
09:40	7	4.00	99.76
10:00	6	3.43	99.82
10:20	7	4.00	99.76
10:40	7	4.00	99.76
11:00	6	3.43	99.82
11:20	4	2.29	99.92
11:40	1	0.57	100.00
12:00	1	0.57	100.00
12:20	2	1.15	99.98
12:40	6	3.43	99.82
13:00	6	3.43	99.82
14:00	7	4.00	99.76
13:40	6	3.43	99.82
14:00	7	4.00	99.76
14:20	7	4.00	99.76
14:40	8	4.57	99.68
15:00	10	5.71	99.50

9. System features

9.1 Reliability

The designed stand-alone solar tracking system is based on a real time accurate calculations and it does not need to find the sun location depending on light sensors or cameras which are not reliable on dusty places or confused when light rays are reflected from nearby obstacles [10, 11]. The system gets its time accuracy from the real time controller (RTC) with 32.768 kHz Crystal. Also, it has an automatic power-fail detect and switch circuitry. Additionally, the use of linear actuators gives the system more stability, linearity, accuracy and cost effectiveness. Stability is achieved by the built in gear inside it, which lets the panel to be fixed after release the power. Linearity is achieved by the linear shift. The used actuator sends 45 pulses per inch which makes the controller free in managing the panel location.

9.2 Flexibility

The system is designed with important features which allow the user to install it in any location. In the initialization phase the system asks some questions on the LCD screen and the user has to answer these questions for better tracking accuracy. For example, the system will ask for the location of the solar panel, the local time, the date of year...etc.. In addition, the system is compatible with all types of linear actuators which may have different pulse counts per inch. This compatibility comes from the flexibility of the build software. The system will ask for the number of pulses per inch for the used actuator and the range of tracking angle. Furthermore, the flexibility comes from the used MCU which can be updated at any time with nonvolatile program and data memories 32 Kbytes of in-system self-programmable flash.

9.3 Power saving

The majority of the present trackers move the panel horizontally (azimuth direction) then vertically (elevation direction) to reach the new position. Hence, every time the sun moves both actuators need to be adjusted which means the system spends more power and needs more time. The proposed system moves the panel in the polar direction periodically with only one daily adjustment of the tilt angle and hence it will spend less over all power.

10. Conclusions

The system new feature of implementing the astronomical equations for determination of the sun location allows the user to install this tracker in almost any place on earth. The conducted practical measurements showed that the system to be reliable, precise, flexible and cost effective.

Furthermore, the flexibility of the proposed design makes this tracker compatible to be part of a solar farm, where large number of such trackers can be controlled from one master controller. In fact work in this direction is being conducted by the research group and some encouraging findings have already been obtained.

Acknowledgements

The first author, Fawzi Al-Naima acknowledges the financial support offered by the IIE Iraq Scholar Rescue Project.

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