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DESIGN OF A COST EFFECTIVE EDUCATIONAL INSTRUMENT TO STUDY SOLAR TRACKING STRATEGIES

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Abstract. *Solar energy has been drawing more and more attention due to the increasing pollution and shortage of fossil fuels. As the sun´s position changes throughout the day, a solar tracker is an efficient method to increase the energy production. This paper presented herein describes a microcontroller based project easily extended for controlling and monitoring solar trackers for research and educational purposes. A dual-axis solar tracker has been employed in standalone photovoltaic system. Around 30% annual energy production gains will be expect in similar commercial solar trackers, nevertheless, commercial trackers are often prohibitively costly for standalone and decentralized photovoltaic systems. The proposed tracker design is built from recycled materials that are readily available to promote a low cost solution. Few specialized parts are made in router machine using a computer-aided design and manufacturing software. Comprised of a 0.15 m linear actuator coupled directly to stepper motor, the tracking mechanisms would pair well with the single robot scheme since the lead screws for the linear operation prevent back drive without braking. The solar tracker geometry fully exploits solar trajectory with 270° maximum range. The microcontroller software employs the mathematical formulas to determine the sun position. The system calculates constantly the declination angle and clock angle and the tracking process continues until sunset. Field tests demonstrated low error rates in the tracking capability to what would be expected with the use of a commercial PV solar tracker.*

Keywords: *Solar Photovoltaic, Solar Tracker, Educational Instrument*

1. INTRODUCTION

Approximately 80% of the global energy consumption are from conventional fossil fuel based (Bahrami *et al.*, 2016). In fact, the pollution of fossil fuels and the world growing energy demand are becoming the renewable energy (RE) sources increasingly viable means of power generation. The RE sources are the best available options to fulfill the world demand of power due to their advantageous features like availability and environmental friendly. Solar systems, wind power generation systems, biomass, fuel cell, micro-turbine, hydro and geothermal are currently been promoted as deployable sustainable alternatives.

Among renewable energy resources, solar energy source is one of most promising and capable of contributing to global energy generation mix in the nearest future (Bahrami *et al.*, 2016). Solar energy is by far the largest exploitable resource, providing more energy in 1 hour to the earth than all of the energy consumed by humans in an entire year (Lewis, 2006). Therefore, solar energy stands out with the most important renewable source of energy (Eldin *et al.*, 2016). Concentrated solar power (CSP) and solar photovoltaic (PV) are viable means of grid-scaled power generation. Solar photovoltaic has received wide spread attention and its installation capacity is expect to reach 800 GW by the year 2030 (Elbaset *et al.*, 2016). The increased growth of PV systems is due to various advantages such long life, ease of generation at the point of use and low maintenance. Despite these advantages, the power conversion efficiency of solar PV is approximately 30 to 40% (Solangi *et al.*, 2011) and the high installation costs are hindering the utilization of PV power. In Addition, as the sun´s position changes throughout the day, PV sources are affected by the installation Azimuth and elevation angle. Consequently, a solar tracker is needed for tracking the solar path from sunrise to sunset, increasing the energy production. All CSP systems require the use the solar trackers, while not a necessary component in PV systems.

It has been a concern weather to install PV tracking system or is it better to install a fixed PV? Recently, Fathabadi *et al.* (2016) showed that solar trackers can increase between 20% to 50% power gain when applying a solar tracker to

PV system in comparison with using a fixed PV system. Earlier work (Clifford and Eastwood, 2004) using a variable elevation solar tracker has shown that up 40% extra power can be produced per annum. Conversely, it is not all good in installation of a tracking system: the initial cost a tracking system is higher than a similar fixed system due to installed motors and moving joints; a sun tracker could be useful on clear-sky days and it is unnecessary on cloudy days. In summary, different aspects must be investigated to define the better approach.

In this context, the objective of this research is a development of a solar tracker which can be used as an educational instrument to teach students how to improve its efficiency and effectiveness. The simple mechanical tracker could be easily repaired with basic workshop facilities. Likewise, the design of a cost effective educational instrument can improve the researches about the feasibility of a tracking systems in different regions of the world. In many instances, a commercial tracker is prohibitively costly to education purposes. However, the prototype presented herein is a design for a low profile solar tracker, in other words, it is built from recycled materials that are readily available to promote a low cost solution. The proposed design is built to determine the various parameters of a solar PV tracker for different solar tracking strategies. The section 2 describes the sensorless tracking strategy proposed for a flat PV system.

2. DESCRIPTION OF SOLAR TRACKER

2.1 Declination clock mounting system

In this paper, the proposed tracker is named declination-clock mounting and it has two freedom degrees. The primary axis is located in east to west direction. This axis enables the panel to vary timely according to the seasonal motions of the sun (Yao *et al.*, 2016). The rotation angle for the primary axis is named declination angle (θ_{DA}). The secondary axis is located in North-South direction. This axis enables the panel to vary timely approximately 15º per hour. Rotation angle for the secondary axis is named clock angle (θ_{CA}). The declination angle and clock angle are shown in Fig. 1.

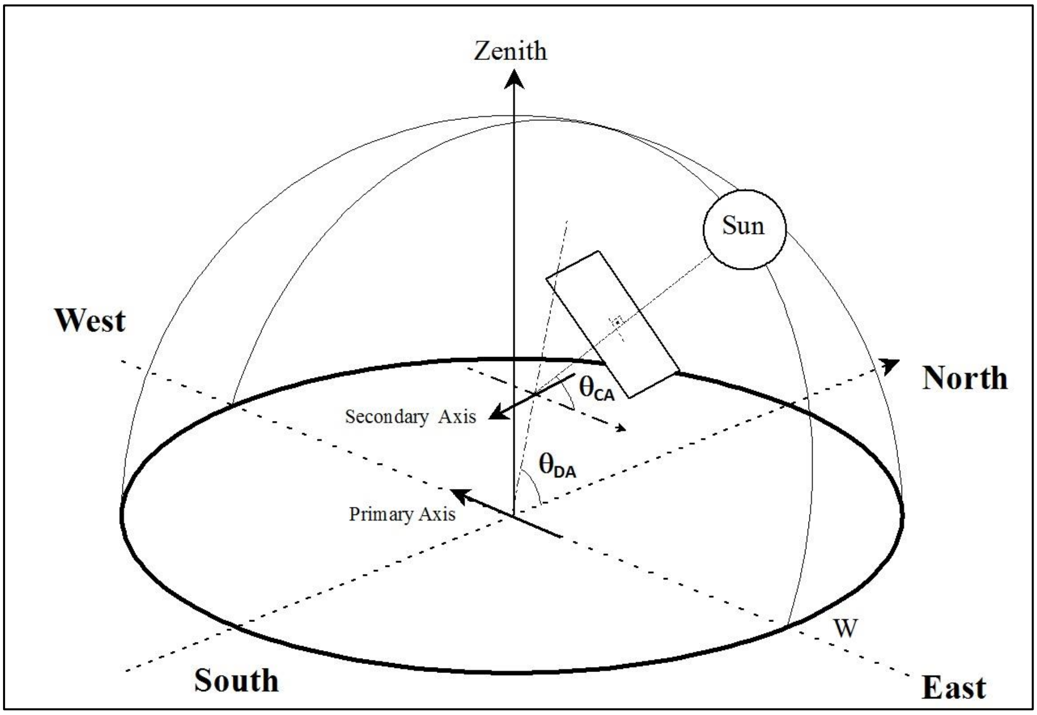

Figure 1. Declination angle θ_{DA} and clock angle θ_{CA} in the proposed mounting system

Orientation of two-axis trackers can be descripted using the spherical coordinate system comprised of azimuth (α) and elevation (γ) (Barker *et al.*, 2013), commonly referred to as the alt-az system (Prinsloo and Dobson, 2015). The azimuth and elevation can be viewed by an observer on the Earth as shown in Figure 2.

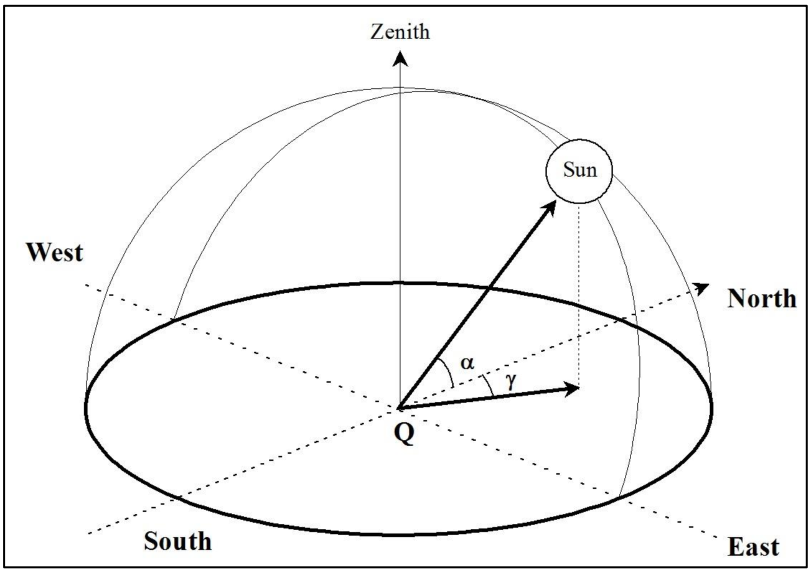

Figure 2. Observer at location Q showing solar azimuth γ and elevation α angles

The declination angle is the angular position of the sun at solar noon with respect to the equator is obtained:

$$\sin(\delta) = \sin\left\{23.45 \sin\left[\frac{360}{365}(\mathrm{d}-81)\right]\right\} \tag{1}$$

where δ is the declination angle and d is the day number of the year. The altitude angle denoted by α is obtained as:

$$\sin(\alpha) = \sin(\delta) . \sin(\varphi) + \cos(\delta) . \cos(\varphi) . \cos[15° \,(LST - 12)] \tag{2}$$

where φ is the latitude of solar tracker and LST is the local solar time. The azimuth angle denoted by γ is found as:

$$\cos(\gamma) = \left\{\left(\frac{\sin(\delta) . \cos(\varphi) - \cos(\delta) . \sin(\varphi) . \cos[15°. (\mathrm{LST} - 12)]}{\cos(\alpha)}\right)\right\} \tag{3}$$

Based on Eq.2 and Eq. 3, the theoretical curves are plotted in Fig. 3.

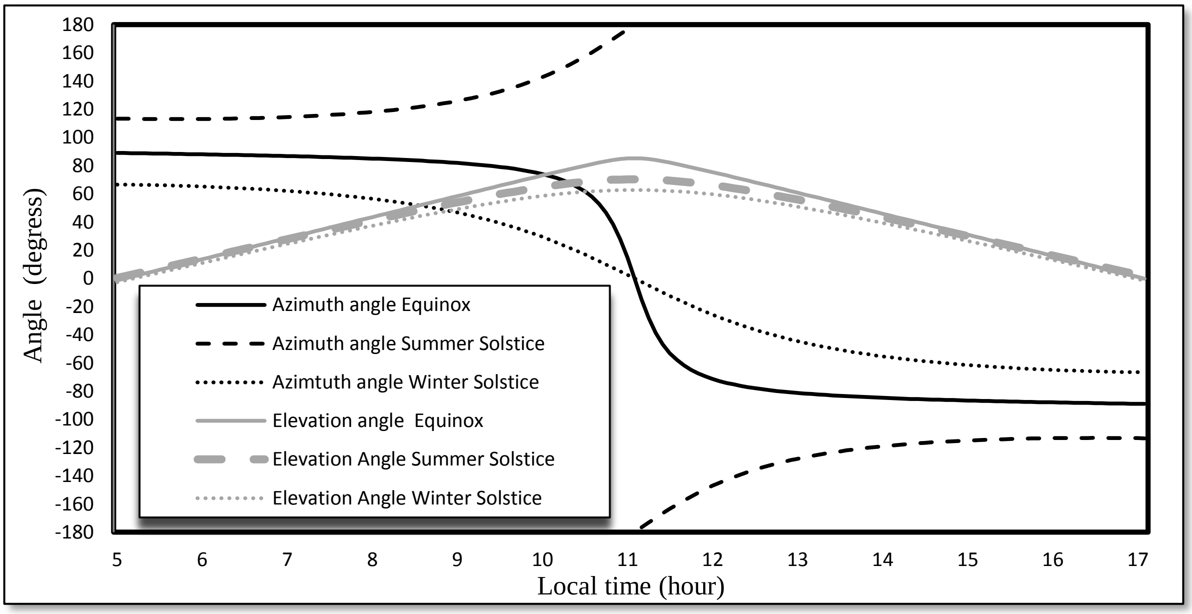

Figure 3. Diagram of angle versus local time on equinox day, summer solstice day and winter solstice day in Fortaleza

The azimuth angle is between 0° and 180º in the morning and between -180º and 0º in the afternoon. A solar tracker keeps perpendicular the incoming solar radiation, compensating for both changes in sun altitude angle and changes in azimuth. As shown in Fig. 4, the rotation angles of the solar tracker are based on azimuth angle and elevation angle.

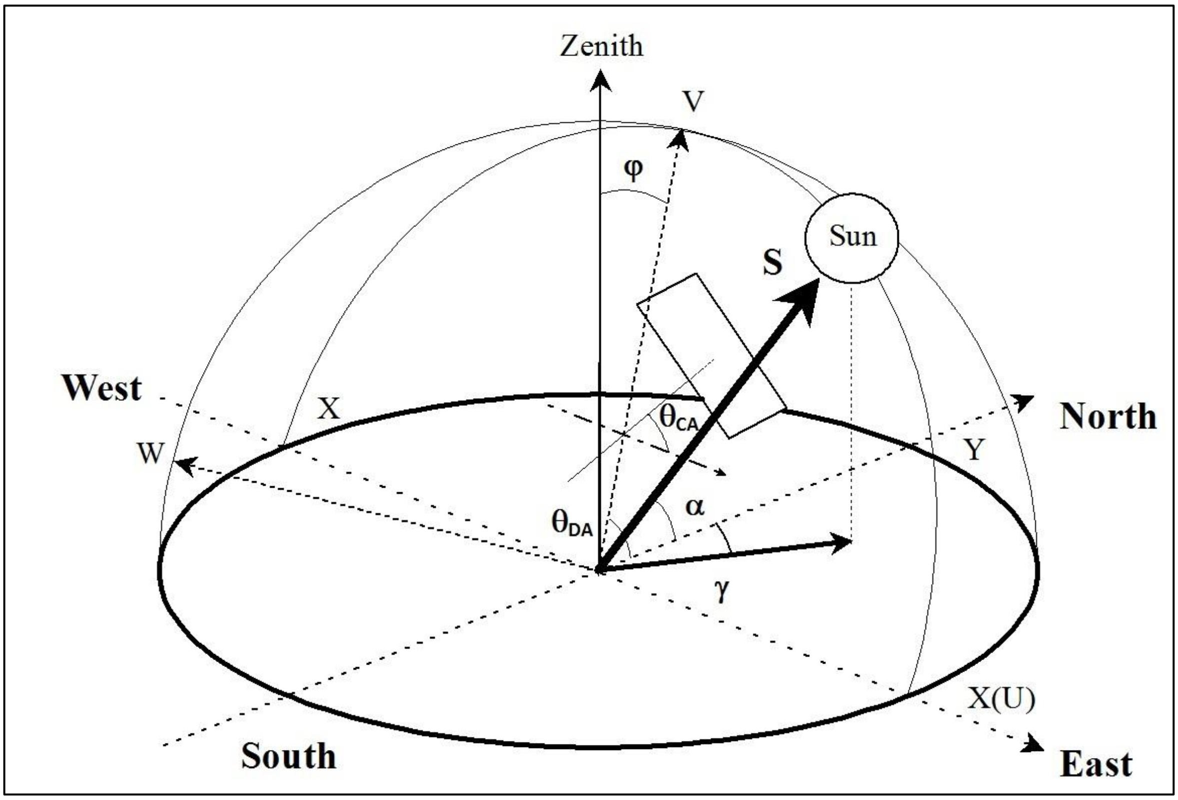

Figure 4. Schematics of vector S in the declination clock mounting system on equinox day

For the analysis of declination-clock mounting system are established two coordinate systems (Yao *et al.*, 2016), named XYZ-O and UVW-O. The vector S is obtained in the coordinate system of XYZ-O as:

$$S = (\sin\gamma \cos\alpha, \cos\gamma \cos\alpha, \sin\alpha) \quad (4)$$

As depicted in Fig. 4, the vector S can be expressed in the coordinate system of UVW-O as:

$$S_{UVW-O} = (\sin\theta_{CL} \cos\theta_{CL}, 0) \quad (5)$$

The vector S can be expressed in the coordinate system of XYZ-O as:

$$S_{XYZ-O} = (\sin\theta_{CL}, \sin\theta_{DA} \cos\theta_{CA}, \cos\theta_{DA}\cos\theta_{CA}) \quad (6)$$

Finally, the angles θ_{DA} and θ_{CA} can be expressed as:

$$\tan(\theta_{DA}) = \cos\gamma \cot\alpha \quad (7)$$

$$\sin(\theta_{CA}) = \sin\gamma \cos\alpha \quad (8)$$

Finally, the Fig. 5 shows the declination angle and the clock angle on equinox day, summer solstice day and winter solstice day in Fortaleza where the latitude is 3.87º south.

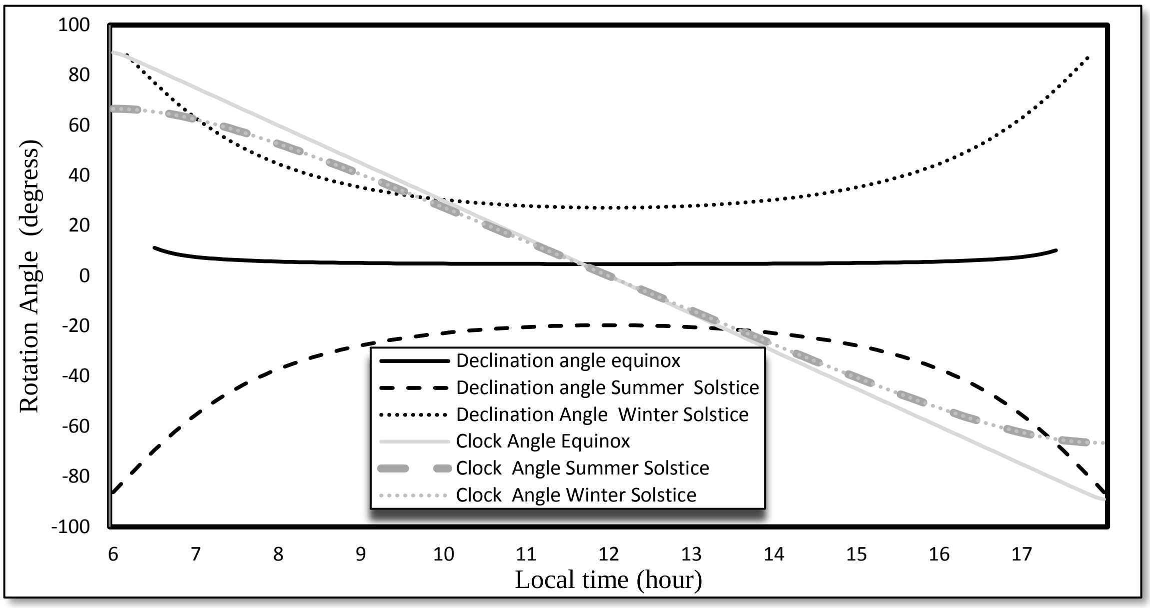

Figure 5. Diagram of declination angle θ_{DA} and clock angle θ_{CA} versus local time on equinox day, summer solstice day and winter solstice day in Fortaleza

2.2 Tracker Design

The designed solar tracker has two linear actuators and two connecting rods which are used to drive the solar collector array. Comprised of a 0.15 m linear actuator coupled directly to stepper motor, the tracking mechanisms would pair well with the single robot scheme since the lead screws for the linear operation prevent back drive without braking. The sliding motion occurs directly between the sliding part and the screw. In addition, the linear actuator is coupled to a low cost screw for operation in both angles θ_{DA} and θ_{CA}. The stepper motor having holding torque of the 0.31 N.m, however holding torque of motor has magnified by a factor of 5 in the actuator . Other parts of the actuator are machined by a milling machine and the main material utilized is polyamide which exhibits unique mechanical performances combined with outstanding resistance to heat, oxidation and weathering. The rods are made up recycled materials like galvanized steel used in legs of student chairs. The solar tracker geometry fully exploits solar trajectory with 270° maximum range of clock angle and 90º maximum range of the declination angle. Figure 6 shows the whole solar tracker and a detailed image of the actuator.

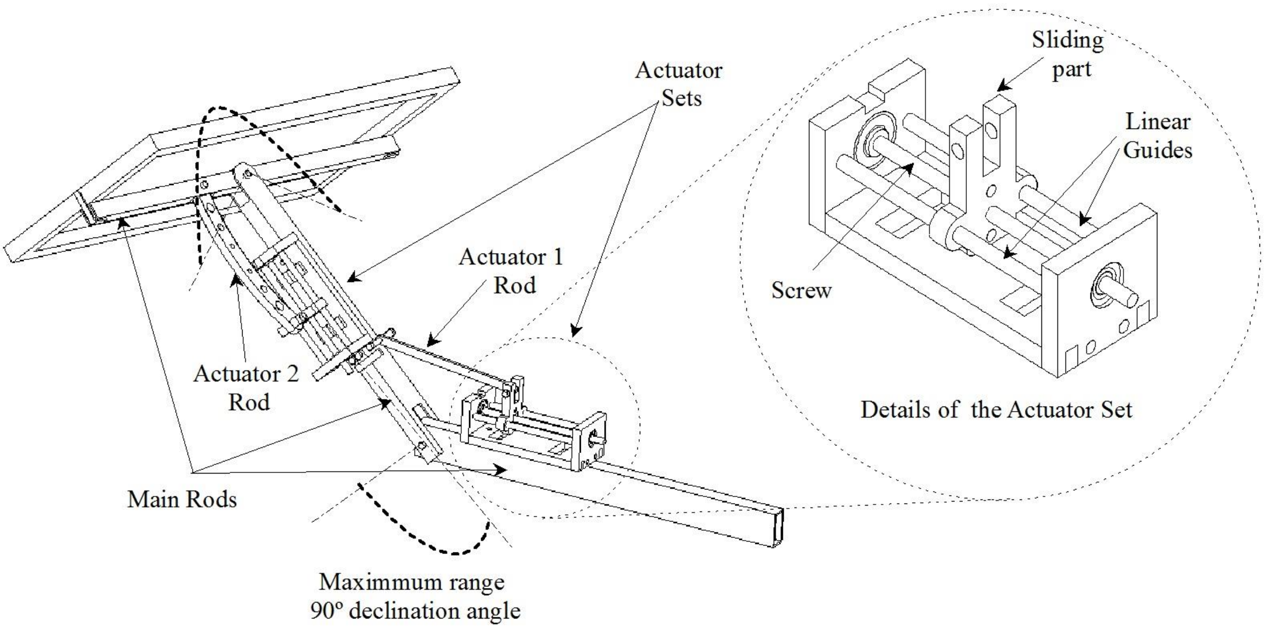

Figure 6. Structure of PV system constructed to implement the proposed cost effective solar tracker

2.3 Tracking example strategy

In flat panel systems, the energy contributed by direct beam sunlight drops off with the cossine of angle the sun light and the panel . The power loss due to misaligment is obtained as (Prodham *et al.*, 2015):

$$L = 1 - \cos(i) \tag{9}$$

Where L is the power loss (%) and i is the angle of incidence. Figure 7 shows the direct power loss due the mislignament of PV panel.

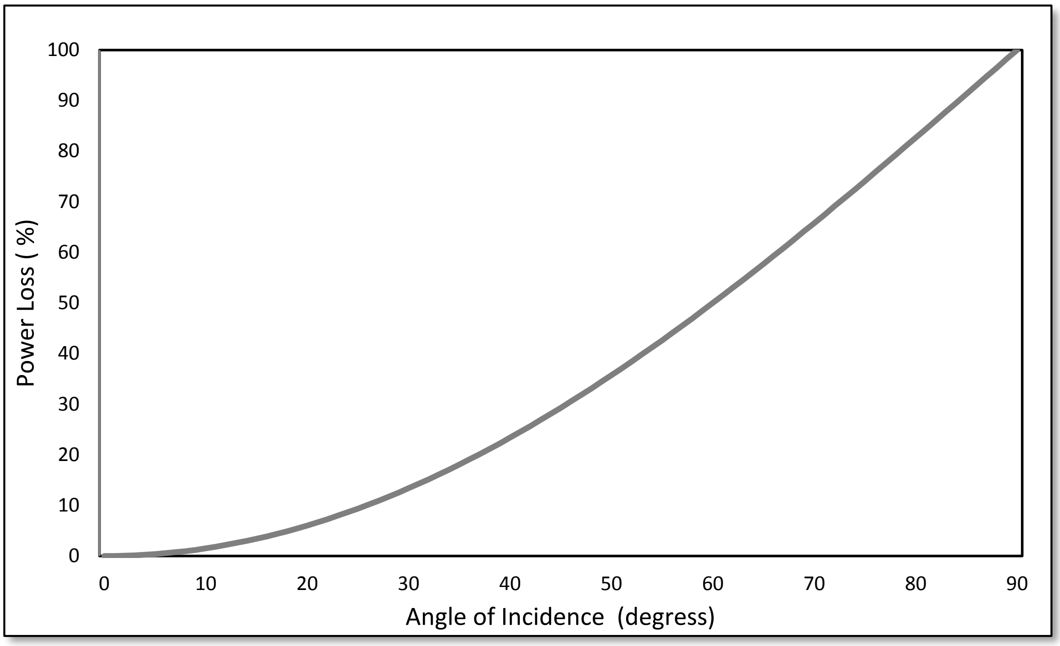

Figure 7. Diagram of Power loss due misalignment of PV panel

A simple and low-cost tracking strategy is developed in this project. The declination angle is adjusted once a day so the direct sun beam is perpendicular every day at noon. As shown in Fig.5, the elevation angle range is 61.85º on winter solstice day and its range is 69.05º on summer solstice day, consequently the maximum power loss at sunrise or at sunset is approximately 45%. However, the angle of incidence decreases to 0º at noon that makes its power loss value equal to zero. On the other hand, for most of the tracking duration the clock angle varies at an almost constant speed of 15 per hour every day. So the equations concerning the two rotation angles can be simplified as follows (Yao *et al.*, 2014):

$$\theta'_{CA} = \omega \tag{10}$$

$$\theta'_{DA} = 90 - \alpha_{noon} \tag{11}$$

Where θ'_{CA} is the simplified clock angle, θ'_{DA} is the simplified declination angle, α_{noon} is solar elevation angle at noon and ω is solar angle.

2.4 Tracking circuit

With the purpose of study a cost effective solar tracking, a much simpler tracking strategy has been proposed for a flat PV panel. A low cost circuit is based on microcontroller PIC16F877A which can control two stepper motors. Two Drivers DRV8825 have been used, one for driving the declination angle motor and another for driving the clock angle motor. The microcontroller has been connected to each driver through the two wires. It calculates the number of the pulses which is needed to each stepper motor driver producing the two control signals to be supplied to the stepper motors drivers. Two NEMA 17 stepper motors with holding torque of 0.31 N.m have been used. There are two buttons to set the current time which to be showed in a liquid crystal display (LCD). In each 5 minutes it calculates θ_{CA} angle and everyday it calculates θ_{DA} angle. In detail, the microcontroller has been connected to a data acquisition system over a serial communication RS 232. External circuit produce two main signals from PV panel, that is, the voltage value and current value which to be turn into digital signals by analog-digital converters in the microcontroller PIC16F877A. A computer stores the data for future tracker efficiency analysis as can be seen in section 3. The solar tracker circuit is shown in Fig. 8.

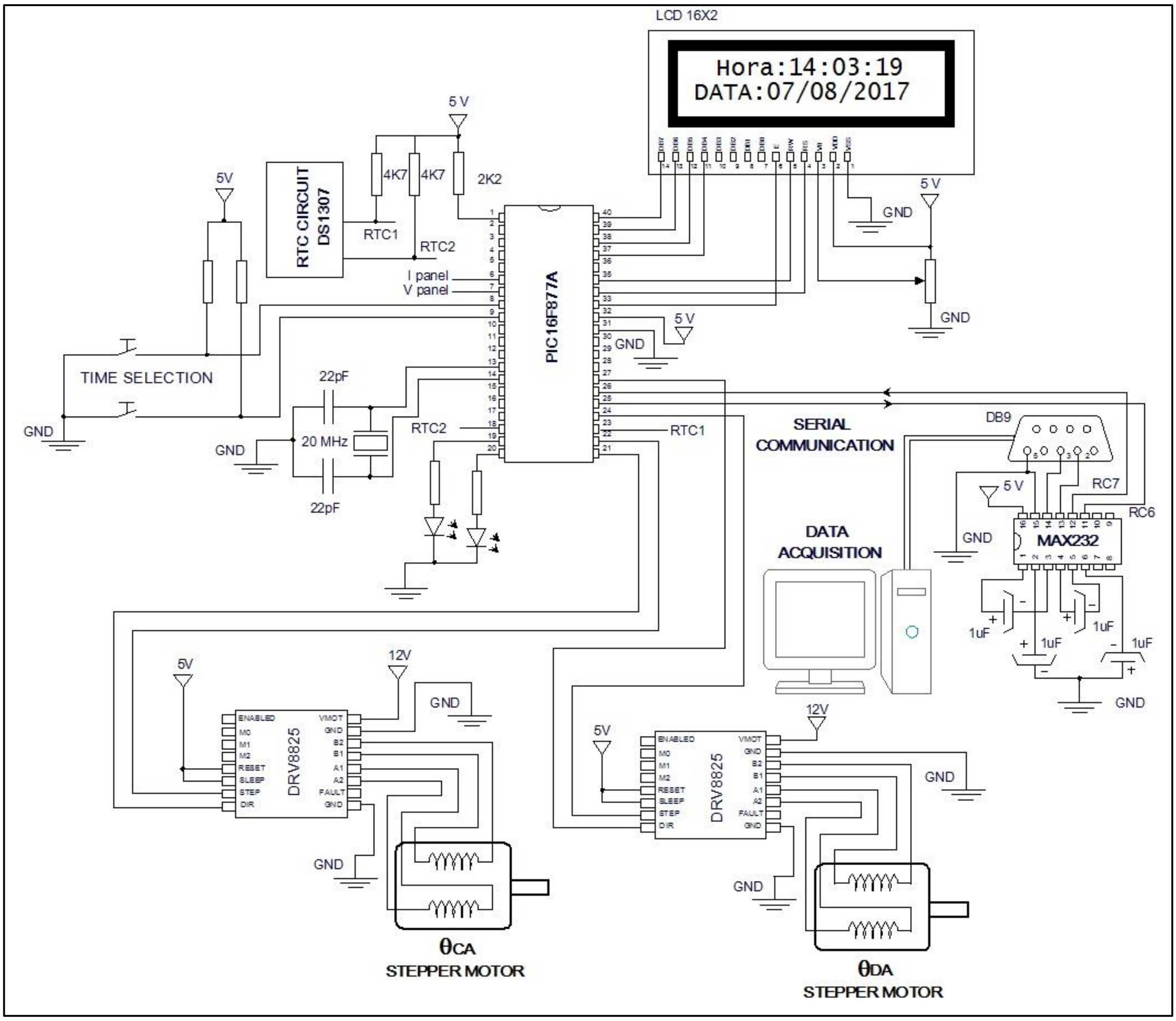

Figure 8. Electrical circuit of the cost effective solar tracking

The microcontroller PIC16F877A has been programmed using C language to numerically solve Eq. 10 and Eq. 11. The position is adjusted based on RTC circuit timer response. Figure 9 shows details of the LCD and adjustment buttons to change the current time in real time clock (RTC).

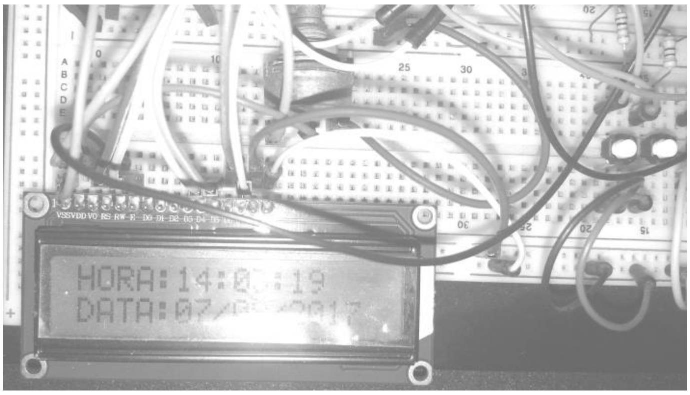

Figure 9. Picture of LCD and adjustment buttons of the solar tracker working circuit

3. EXPERIMENT RESULTS AND DISCUSSION

In order to confirm the validity of the proposed solar tracker, it is necessary to compare the power output of a solar PV in two conditions: First, the power output with a fixed solar tracker adjusted to allow a direct sun light perpendicular at noon. Second, the proposed solar tracker is turned on to follow the sun from east to west, consequently optimizing the amount of energy received. The specifications of PV module are shown in tab. 1.

Table 1. Specifications of the PV panel used in solar tracker

Specifications	Nominal Value
Short-circuit current I_{SC} (A)	0.82 A
Open-circuit current V_{OC} (V)	22.1 V
Output power at MPP(W)	14 W

The tracker is set in Fortaleza, where the latitude is 3.87º south and the longitude is 38.54º west. The azimuth range approximately from 113.35º to -113.35º on winter solstice day and it varies approximately between 66º and - 66º on summer solstice day. It is also worth highlighting that elevation angle varies between 0 and 61.85º north on winter solstice day and it varies between 0 and 69.05º south on summer solstice day. The proposed solar tracker position is shown in the Fig. 10.

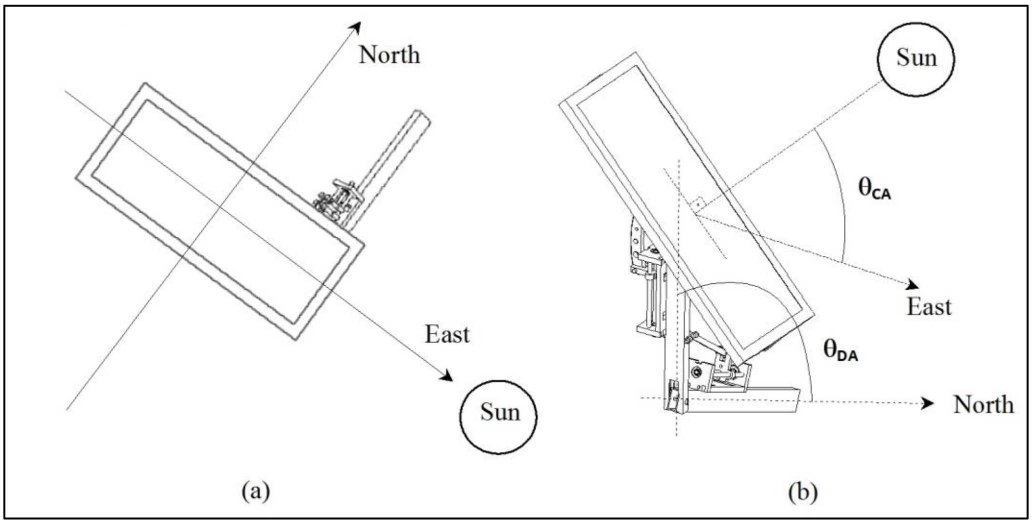

Figure 10. Schematic of the solar tracker position showing declination angle θ_{DA} and clock angle θ_{CA}: upper side view in (a) and isometric view in (b)

The solar trackers presented herein is a versatile project, therefore it can be installed on the roof, ground, and walls. Figure 11 shows the solar tracker on the roof in Fortaleza, Brazil.

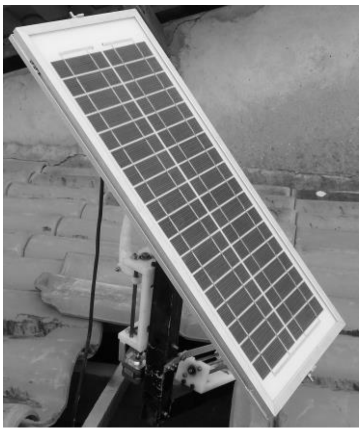

Figure 11. Picture of the PV panel on proposed solar tracker installed in Fortaleza, Brazil.

The output power of a fixed solar panel is tested in comparison with the output power of a tracker solar panel. These two PV modules were measured from hour to hour in daylight on August 07, 2017. The data stored in data acquisition system is shown in Fig. 12.

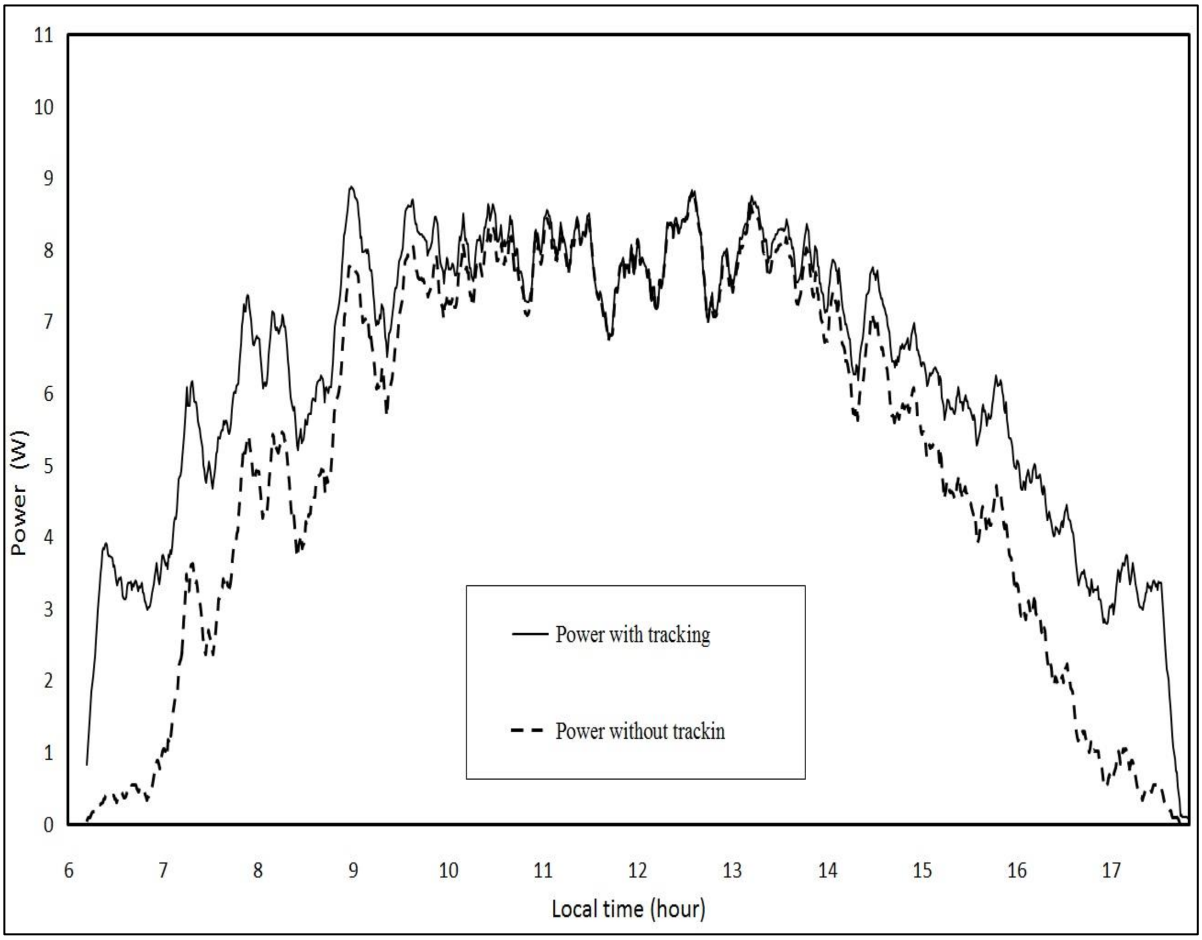

Figure 12. The measured of power versus time for the two cases: tracking the sun and no tracking the sun in Fortaleza, Brazil.

The benefits of tracking the sun are substantial. The proposed solar tracker has the potential to increase solar panel efficiency by up to 20.1% in according Fig. 12. The sensorless tracking strategy shows an obvious increase in PV power output compared to the fixed one and it is independent from external disturbances and weather conditions such as cloudy sky.

4. CONCLUSIONS

A cost effective educational instrument to study solar trackers has been designed and implemented successfully. In this study, a sensorless dual-axis solar with new actuation geometry has been built to find sun direction where the maximum value of solar energy is captured. The tracker was made up recycled materials and field results indicate the benefits of tracking the sun are substantial to increase solar panel efficiency by up to 20%.

Although it was used a low power module, the output power has the possibility to be higher than 14 W proposed, that is, the solar tracker is designed to work with different types and sizes of PV modules and allow for relatively easy module swapping. There are many strategies can be used to improve the energy efficiency. The contribution of this work is enables students and faculties to understand many tracking strategies as the sensorless strategy which is independent from external disturbances and weather conditions. However, other strategies using the proposed solar tracker must be investigated to define the better approach.

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