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Design, Implementation and Evaluation of a Solar Tracking System Based on a Video Processing Sensor

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Abstract— The amount of solar energy captured by a sun collector determines the output power generated for thermal or photovoltaic applications. Hence, accurate solar tracking systems have an important role in the performance of solar collecting technologies. Although, more than 20 years of research in this filed, low cost and simple tracking systems that precisely keep the angle of view through the sun trajectory, is still a challenge that must be met by designer to incorporate it in a practical system without compromising accuracy. In this article the design, implementation and evaluation of a compact two-axes solar tracking system is presented. The system consists of a video processing based sensor connected to a microcontroller that computes a sun-positioning algorithm. The developed structure, by eliminating expensive computing systems, allows closed loop solar tracking as simple, low cost with minimal configuration. The evaluation results show solar tracking average accuracy of 0.0135 degrees for the azimuth angle and 0.0196 degrees for the zenith angle.

Keywords— Solar, Tracking System, Video Processing, Microcontroller, embedded.

I. INTRODUCTION

The sun has an apparent motion with respect to a particular orientation of a plane on the earth, which can be described in terms of angles [1]. The first angle goes from east to west and it is called azimuthal angle, the second angle is the sun elevation or complementary angle called the zenith angle. A solar tracking system must orientate the sun collector moving its collecting surface in these two angles. Because these movements a solar collector will not have fixed position [2]. A solar tracking system plays an important role in solar collectors since the maximum received solar radiation depends on its precision and accuracy [3]. In a two-axis photovoltaic solar tracking systems it is possible to generate more than 40% energy compared to a fixed [4-7]. In the case of solar collector with concentration, the tracking system must be very precise, to ensure good thermal behavior [8]. Over time different types of system structures and control algorithms have been proposed for positioning solar equipment, such as: closed-loop, open loop and hybrid systems [9-13].

On one hand, a tracking open loop system, dose not compare the control variable with a reference, that is, the controller is based on a mathematical model where the sun position is calculated by computing algorithms [14 -17]. On the other hand, a tracking closed loop system is based on feedback control, operational amplifiers (opams) and light dependent resistor [18-20] or phototransistors [21-22] sensors are used for it low cost implementation. Operating principle for both of the previously described tracking systems consist of two or more photosensitive elements strategically accommodated in a geometrical body, which partially or completely is shaded according to the sun position, this allows to obtain a sensor-output signal proportional to the solar radiation incident on each sensor, hence the positioning error are calculated, and consequently the controller performs the corresponding position correction.

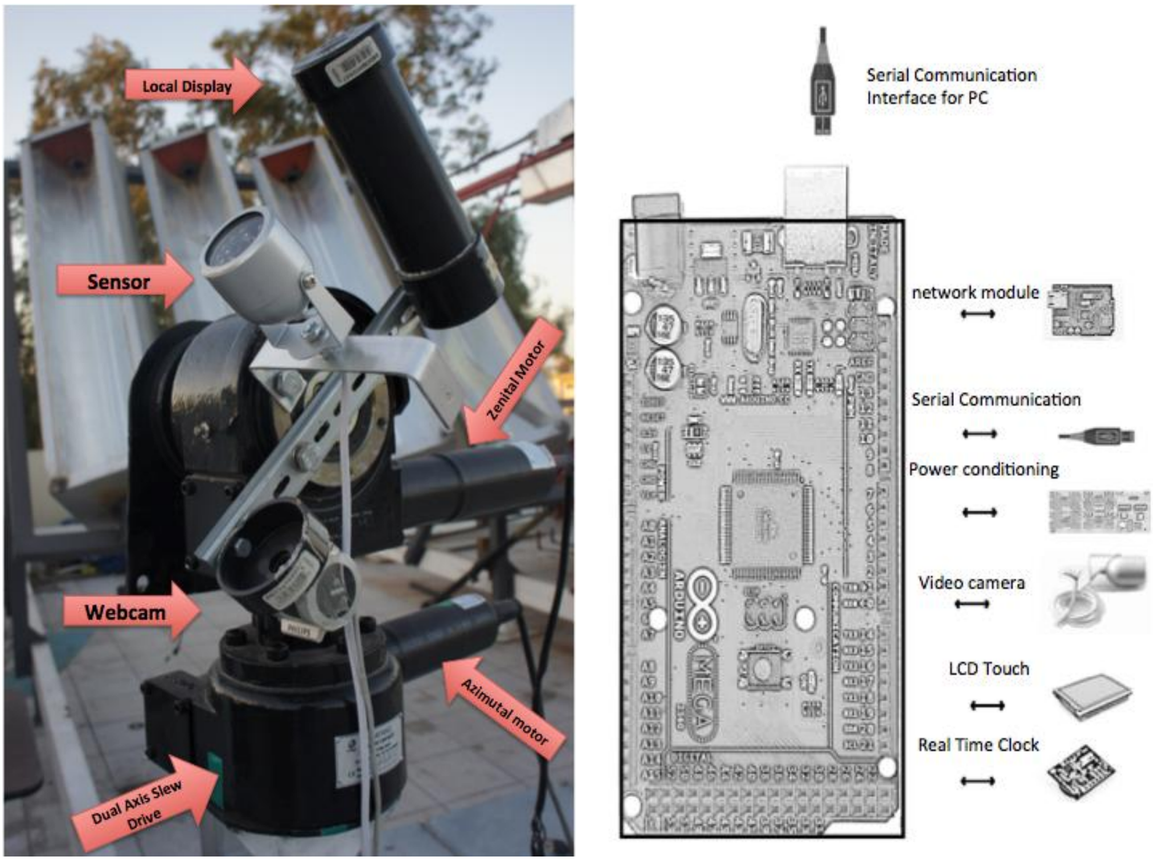
Open-loop systems require components such as encoders, GPS, computing hardware and a precise mechanical structure, which significantly increases the cost. In addition, because the orientation of azimuth and zenith reference angles must be very accurate, sensors calibration and a system-complex installation are required. However, an open-loop system has advantages compared to a closed loop system, because its design is so simple, its user interface is often poor. In addition, a massive installation on a solar field of "n" tracking systems would be impractical to manually manage each device to closed loop. The most notable disadvantage in closed loop track is presented in terms of disturbances, such as a very sensitive controller may range or to obtain a positioning error due to the variation of the solar radiation. Photosensitive sensors also can be disturbed by lighting with a certain wavelength, reflecting sunlight and shaded outside the sensor. Summarizing the advantages of a closed-loop solar tracking systems these are mainly based on its low cost. And its disadvantages can be covered by an open-loop tracking, which has as main feature the high cost.

Another form of closed-loop solar tracking can be realized by using a video camera that captures images of the sun or a sensor shade the captured image is sent to a computer system that performs image processing to detect a position point that is compared with a reference to find an error, thus the controller performs the corresponding control action to correct the error [2,23-24]. In this article the design is presented, implementation and evaluation of a solar tracking system that uses closed-loop video processing. The presented tracking system provides a solution to the common problems that arise in this type of monitoring, such as; the maintaining of a minimal viewing angle, lack of an easy user interface and the associated high-cost of using complex computing equipment. The developed system has significant technical and economic feasibility to be used in a wide range of solar energy applications that require solar tracking.

II. SOLAR TRACKING SYSTEM

The tracking system consists of an electronic device interconnected to an electromechanical structure, which allows positioning a reference surface. Fig. 1(a) shows a dual-axis slewing drive, which means two 24 volts direct-current motors that allows tracking in azimuth and zenith angles. At the top of Fig. 1(a) the solar tracking sensor can be seen, the webcam is used to evaluate the tracking error, and a pipe-tool is used to check the structure focus (local display).

The hardware implementation of the monitoring system is performed by using a low-cost embedded device that consists of a 256016au microcontroller from Atmega. This microcontroller bases its operation on the Arduino platform. Fig. 1(b) shows the solar tracking architecture comprises by the microcontroller connected to a user interface, sensors and a conditioning stage.



a) **b**)

Fig. 1 Solar tracking architecture; a) Experimental system. b) Architecture of electronic solar tracking.

A. User Interface

The user interface consists of a liquid crystal touch screen, which communicates by serial port with the microcontroller to display and navigate the next menu of options:

1. Run automatic sun tracking.
2. Manual mode to operate in isolated events, either for maintenance or adjustment of the electromechanical structure.
3. Adjustment of parameters such as time, date, motor speed and network data.

In order to facilitate parameters setting and the selection of control options an interface to a computer is realized using the USB port or a network module (Ethernet or Wi-Fi). The interface can be monitored locally or remotely through an application installed on the computer, a tablet or a smart-phone. In addition, the device can be adapted to a new applications, for example, in the case of a PV system, the microcontroller can read all sensors and send data through the serial port working as a slave manipulated by a second or third main controller. The real time clock is used to synchronize the solar positioning algorithm, the storage of data and the serial communication devices.

B. Motor Drivers

The electric motors that move the tracking mechanism are activated through a power amplifier, which contains 3 inputs. The first two inputs are a control and a rotation signals. The third input is a PWM (Pulse Width Module) used for the speed of the motors variation. These signals are sent to an electronic arrangement that verifies a valid direction. The next stage has optocouplers to isolate the electronic digital signal from power circuits, and the end of the circuit a traditional H-bridge transistor-based is used to drive the motors (see Fig. 2).

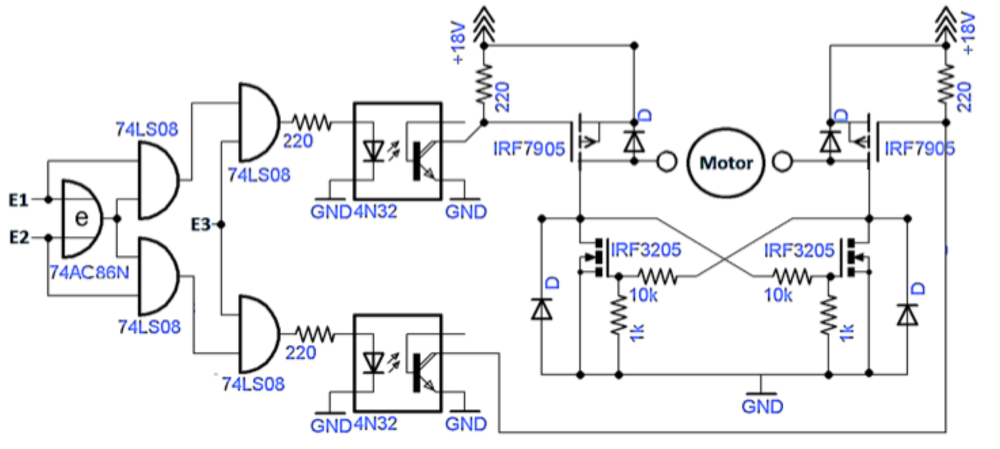


Fig. 2 Schematic diagram of the electronic drivers for motors activation.

C. Solar Tracking System Sensor

Figure 3 shows the solar tracking sensor comprising a NTSC video camera. The video camera is connected to a video splitter LM1881, which detects the time of vertical and horizontal synchronization of composite video signal. The analog comparator ATmega328 on the Arduino-Nano, is used to detect the brightness of the video signal at any given point on time, this information is captured in a memory image pixels that represent a low-resolution monochrome format. As a result it is obtained a matrix of 128x96 img that is described as img(x, y) [25]. On the left side of Fig 3 are four phototransistors in a serial connection with a load resistor. The voltage divider is proportional to the amount of incident solar radiation on each phototransistor; the microcontroller analog channels read these potential differences.

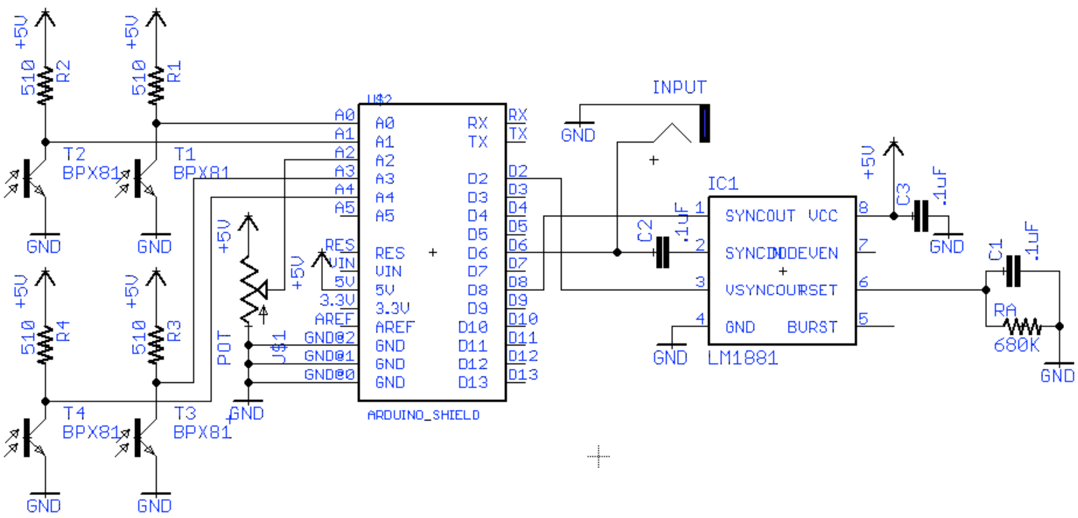
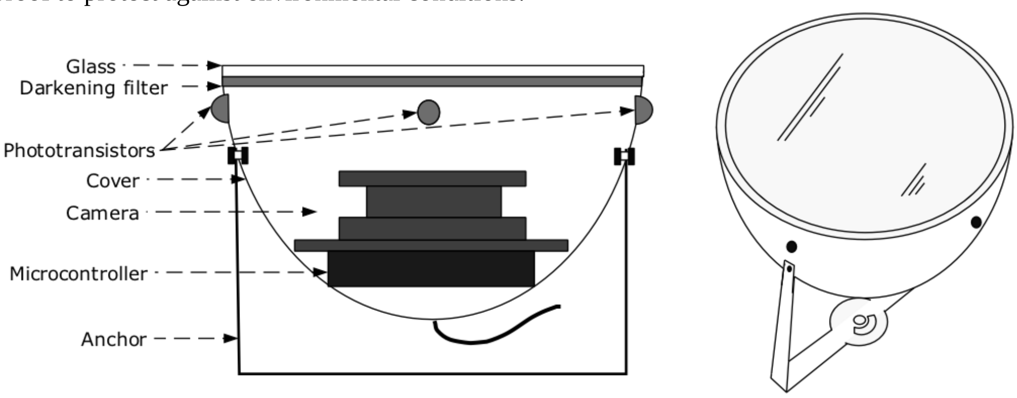


Fig. 3 Schematic circuit of a video processing sensor.

Fig. 4 shows a schematic diagram of the sensor physical setup. The NTSC video camera is located within a circular housing waterproof to protect against environmental conditions.



a) b)

Fig. 4 Physical setup of a sensor. **a**) Internal view. **b**) External view.

At the top a darkening welding filter is placed to avoid direct exposure to radiation, as it can damage the lifetime video chip. Outside the surface of the housing waterproof two phototransistors are placed in each axis to determine the position of the sun when it is out of the camera-viewing angle.

The solar tracking sensor includes a microcontroller that runs the algorithm shown in Fig. 5. In the first step the sensor arrangement captures the current video frame.

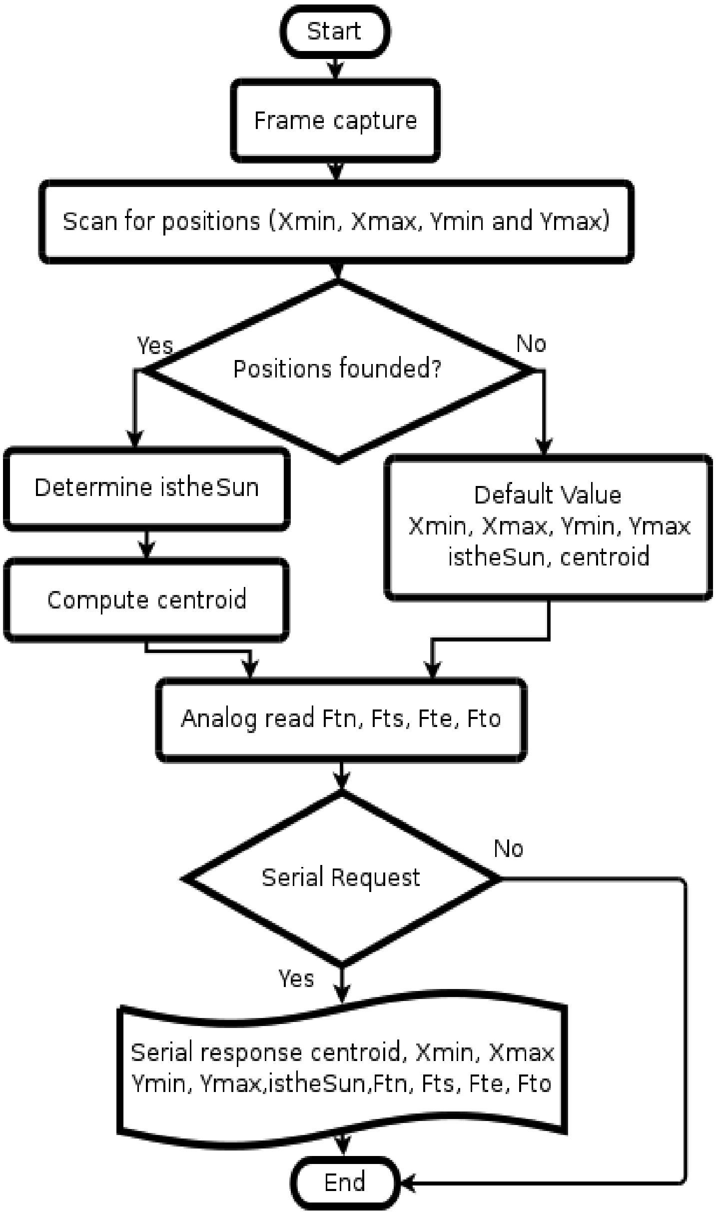


Fig. 5 Flow char of operation of sensor.

Then, the captured image is scanned to find the vertical and horizontal positions (Xmin, Xmax, Ymin and Ymax) of the outer sun pattern. On one hand, if Xmin, Xmax, Ymin and Ymax have different values form they initialized values then a sun patter is captured and the variable "istheSun" is set boolean value "True". Also, the vertical and horizontal positions are used to calculate the centroid c(x, y) of the captured image. On the other hand, if Xmin, Xmax, Ymin and Ymax are equal to the default values then a sun patter was not captured then the variable "istheSun" and the centroid c(x, y) of the captured image are set with default vales. Further after, the variables Ftn, Fts, Fte and Fto from the photodiodes are also captured. Once all variables are registered, the microcontroller check if an external serial communication have been requested, if the answer is yes all variable vales are send to the external guess, if the answer is not the algorithm end. It is important to comment that this algorithm is running in a close-loop to keep the sensor operating all time.

D. Solar Positioning Algorithm

The tracking algorithm runs on the microcontroller Arduino Mega 2560. The algorithm operation is based on the flowchart shown in Fig 6. In the first step the microcontroller send a serial communication request to the sensor controller. Once the communication is established the Arduino Mega 2560 receives from the sensor controller a packet of information that contains the calculated image centroid c(x, y), the vertical and horizontal sun patter positions (Xmin, Xmax, Ymin and Ymax), the value of the variable "istheSun" and the solar radiation values taken for the phototransistors Ftn, Fts, Fte and Fto. If the variable "istheSun" is the boolean value "false" the algorithm uses the values from the phototransistors to track the system until the viewing angle of the camera is reached.

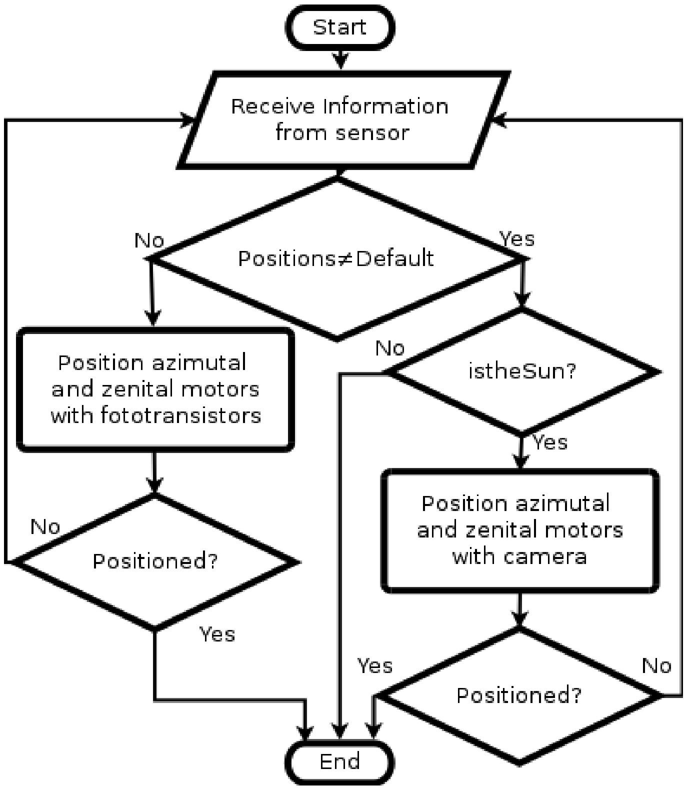


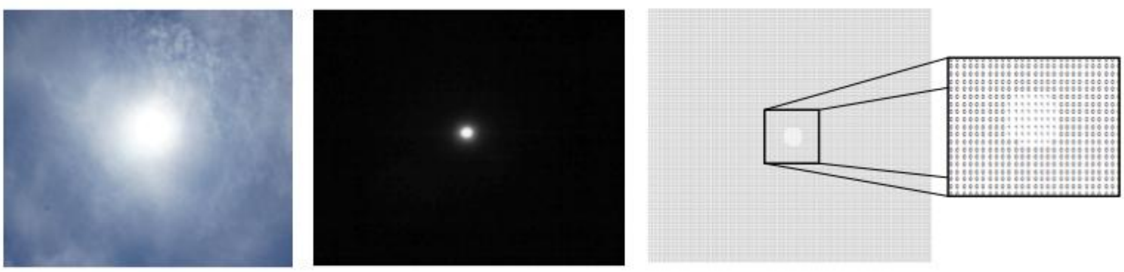
Fig. 6 Algorithm for solar tracking

III. Evaluation of Solar Tracking

To evaluate the operating performance and accuracy of the tracking system, an inclinometer was used to measure the angle of incidence. The measure was realized with a camera connected to a personal computer using the USB interface. The Matlab library functions imaqtools were used to capture the sun images. The camera was set up with a VGA resolution of 640x480 pixels and held on the tracking system with the image processor. The camera images were used to measure the equivalence of pixels to degrees. The centroid of the solar image is the parameter used to indicate the moving sun direction, as well as the point that the image focus is outside the structure. In the capture image the cartesian axes "x" and "y" are initiated at the point f(0,0) = f (WIDTH / 2, HEIGHT / 2) = f (640/2, 480/2). Thereafter, the mechanism moves the position of the structure until the centroid of the solar image converges to f(0.0) (perfect focus). Then the structure started moving in the "x" axis, and with the help of an inclinometer pixels were converted to degrees. Repeating the same procedure for "y" axis also pixels were converted to degrees. Resulting in a pixel resolution of 0.0176 degrees for both axes. The evaluation was made on April 14, 2013, in Mexicali Baja California, Mexico with 32.63167 latitude degrees and 115.44512 longitude degrees. The software on the computer was set up to record the (x, y) focus and the sun vector measurements every 5 seconds. It should be noted that the USB camera was only used to evaluate if the tracking system was working by itself.

IV. Result and Discussion

One of the first tests was to analyze and characterize the sensor, Fig. 7a shows how you see the real picture, the sun can be seen with a radius larger than conventional due to the diffuse radiation generated by the clouds. In Fig. 7b shows the view from the sensor image, and clearly looks like the physical filter that does its job and passes only the most intense sunlight. In the third (Fig. 7c) image observer as you can see the image in memory of the microcontroller, which is a Boolean matrix img [28x96], highlighting the presence of sun in true value. The test was conducted in the presence of a weather cloud and yet the sensor is not affected in the case of a clearly day, the real image of the sun can be observed with a smaller circumference, but the change in the image view from the sensor is not significant.



a) **b)** **c)**

Fig. 7 Image processing by steps. a)Real Image. b) Image from sensor. c)Image from memory of microcontroller

Figure 7 shows the azimuthal angle, the zenith and the sun vector errors *vs* time. The zenith and azimuthal angle errors change its value in multiples of 0.0176 degrees, since it is the resolution in the measurement of the chamber approach angle. The results show a maximum measured error of 0.0353 degrees as well as an average error of ± 0.0135 degrees in tracking the azimuth angle. These errors indicate that the collector was focused in almost all operation time. Meanwhile, the zenith angle had a maximum error of 0.0531 degrees, and an average error of 0.0196 degrees. In this case higher errors were obtained because the sun has a lower travel speed. Hence it takes longer to exceed the controller on-off hysteresis. Also it takes longer to perform the control action. In addition, Figure 7 shows the change of sign of zenith angle. This is because the electromechanical structure follows the sun for about 11:10 hours, with a low solar position that exceeds the elevation of the structure, the mechanism is forced to decrease its elevation to track the sun. Around at 12:37 pm the same phenomenon happened but in reverse. The total error can be determined from the maximum solar vector error resulted in 0.0559 degrees and an average error of 0.0269 degrees. The total error is mostly affected by the zenith angle. Table 1 shows a summary of maximum, minimum and average values obtained in the measurement.

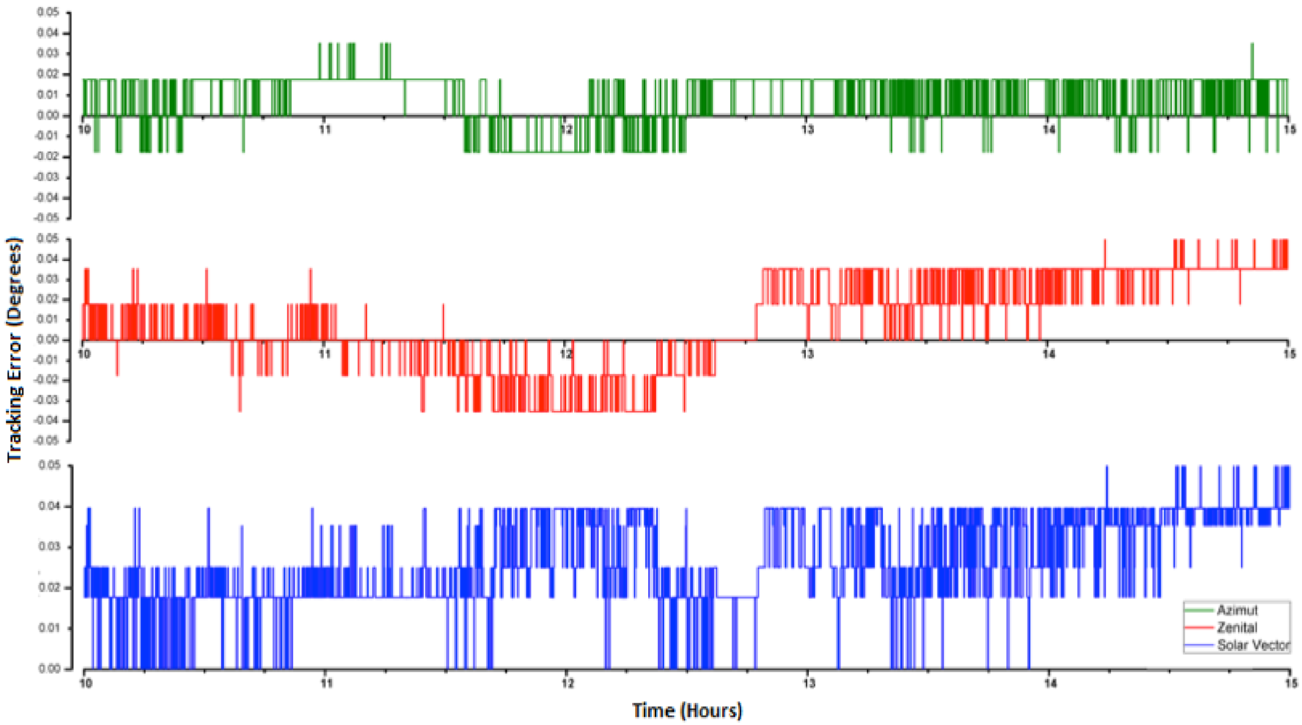


Fig. 8 Measure angle of component and the solar vector.

TABLE I
EXPERIMENTAL RESULTS IN DEGREES

	Azimut	Zenital	Solar Vector
Max	0.0353	0.0531	0.0559
Average	0.0135	0.0196	0.0269
Median	0.0176	0.0176	0.0250
Moda	0.0176	0.0353	0.0176

The evaluation results proved that the sensed parameters from the photoresists are able to track the sun when it is out of the viewing angle of the sensor (camera). Further after, using the camera sensed frame fine adjustment can be realized. Furthermore, the same behavior was observed when different solar radiation intensities shine the video camera.

V. CONCLUSIONS

This article presents the design, implementation an evaluation of a two-axes solar tracking system based on video processing. One of the main advantages of the reported system is that it does not use traditional computing equipment, since its implementation was realized using low cost devices. The used sensor has a wide viewing angle and it is not affected by the variation of solar radiation. The developed user interface is user-friendly, and also has remote access via network, allowing its easy incorporation into a solar field composed by many sun collectors.

Experimental results demonstrated the implemented tracking system to have an average error in the azimuthal angle of 0.0135 degrees, and an average error in the zenith angle of 0.0269 degrees. And a solar vector average error of 0.0269 degrees. In addition, the proposed tracking system addressed the problems presented by this type of equipment, such as; a reduced angle of view, a sophisticated user interface, and a high cost of using computer equipment. With the above demonstrates that the proposed technology is feasible for use in a wide range of applications that require solar tracking such as parabolic trough collector, solar dish, fresnel lens and PV systems.

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