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Technical note

Design and construction of a system for sun-tracking

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Abstract

An electromechanical system to follow the position of the sun was designed and built at the Solar Evaluation Laboratory of the Technical University Federico Santa Maria (UTFSM) in Valparaiso. It allows the automatic measurement of direct solar radiation with a pyrheliometer. It operates automatically, guided by a closed loop servo system. A four-quadrant photo detector senses the position of the sun and two small DC motors move the instrument platform keeping the sun's image at the center of the four-quadrant photo detectors. Under cloudy conditions, when the sun is not visible, a computing program calculates the position of the sun and takes control of the movement, until the detector can sense the sun again. The constructed system was tested in the climatic conditions of the city of Valparaiso, Chile. The presented tracker proves the effective work of a simple and cheap mechanism, which can be adapted to also work with larger following installations like solar cell panels, concentrators, etc.

Keywords: Sun-tracking; Sensors

1. Introduction

Solar radiation can be converted into useful energy directly, using various technologies. It can be absorbed in solar collectors to heat water and can also be converted directly into electrical energy using photovoltaic solar cells.

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Chile lies between latitudes 18° and 55° S. The yearly average solar radiation varies between 2.14 and 5.91 kW h/m^2 d, which is more than sufficient to provide adequate energy for solar thermal applications. The efficiency of sun-tracking solar cell panels can be increased more than two times.

The construction of a mechanism which follows the sun is not a new problem. The first attempt in Chile was completely mechanical, done by Finster in 1962 [1]. Later, Saavedra [2] presented a mechanism with automatic electronic control. It was used to orient an Eppley pyrheliometer. A recent review of the existing systems has been published by Myers et al. [3].

This paper presents the construction of a sun-tracking mechanism for automatic measurement of direct solar radiation with a pyrheliometer (Fig. 1). The actuator has two axes of motion. A computing program was created to calculate the position of the sun under cloudy conditions to ensure correct orientation of the pyrheliometer during those periods. The determination of the error signal and the strategy of control are described. The corresponding electronic schemes are not presented in the article—most of them can be found in [4]. Some results are shown.

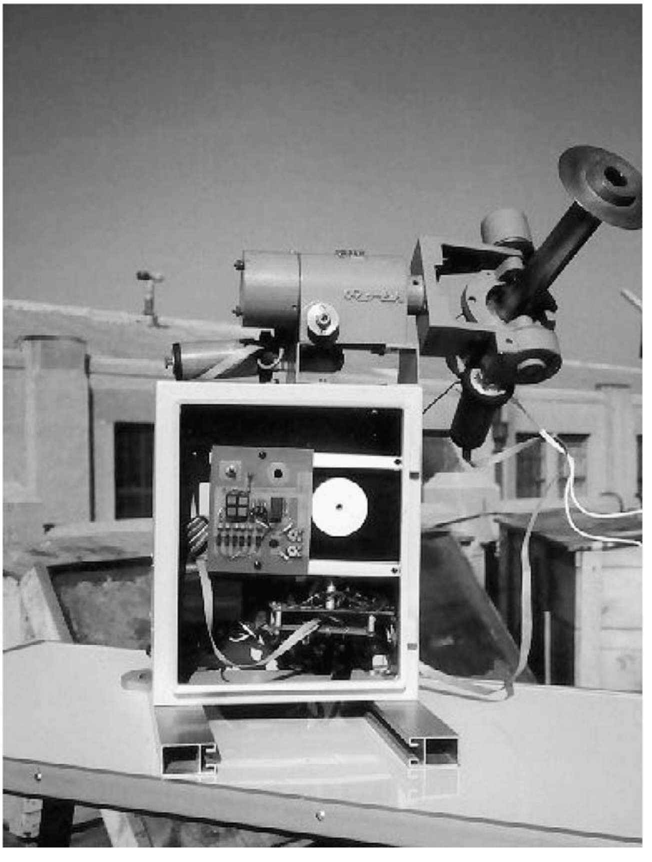

Fig. 1. Automatic sun-following system with a pyrheliometer.

2. System construction

The mechanism (Fig. 2) has two axes of motion: axis HH, 1 (east–west motion) and axis EE, 2 (elevation). The adequate following of the position of the sun by the pyrheliometer, 5, is realized by a combination of both axis motions. The boxes 8 and 9 at the end of axes HH and EE contain one potentiometer and two limit switches each. The potentiometer retransmits the angular position and the switches indicate that the mechanism has reached ±90°. Both axes have different velocities of motion: $v_{EE} = 3600°/h$ and $v_{HH} = 270°/h$. The range of axis EE is from 20° to 150°, and that of axis HH is from −20° to 200°. The difference of velocity is realized using different transmissions for 3 and 4. The sensor, 11, is attached to the pyrheliometer by an aluminum clamp (Fig. 3). A detector, 12, registers the radiation from the sky and generates a binary signal indicating the beginning and end of the day. The whole mechanism is mounted atop box 13, which contains the electronics. Two 3 W DC motors, 6 and 7, are used for axis movement. A special circuit of a controlled half-wave rectifier with the possibility to reverse the sense of rotation of the motors was designed and built [4].

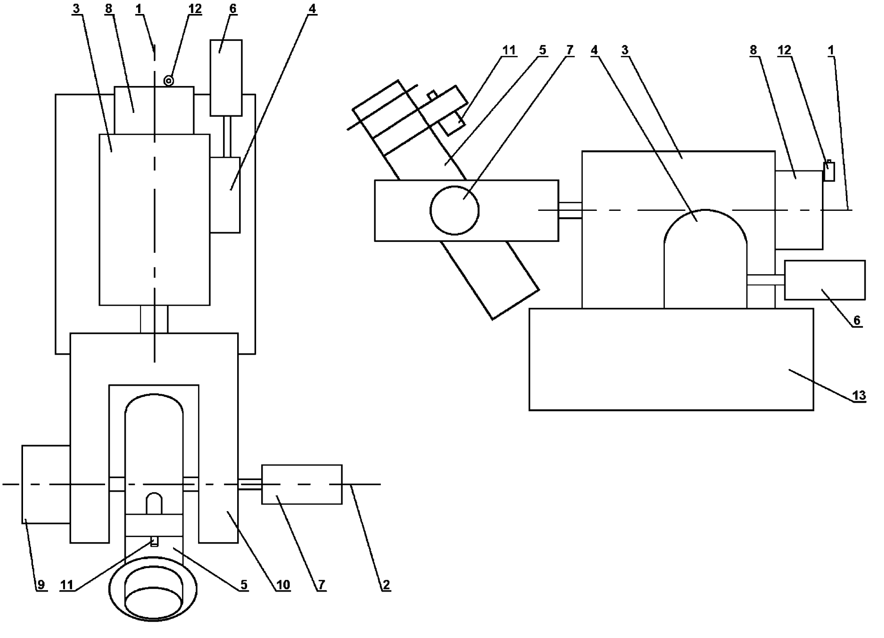

Fig. 2. Scheme of the sun-following mechanism. 1—Axis HH of motion east–west, 2—axis EE of the elevation, 3, 4—boxes of transmission, 5—pyrheliometer, 6—motor of axis HH, 7—motor of axis EE, 8, 9—boxes where the potentiometers and the limiters are connected, 10—support of the pyrheliometer, 11—sensor (four-quadrant photo detector), 12—detector (phototransistor), day–night, 13—box which contains the electronic loop.

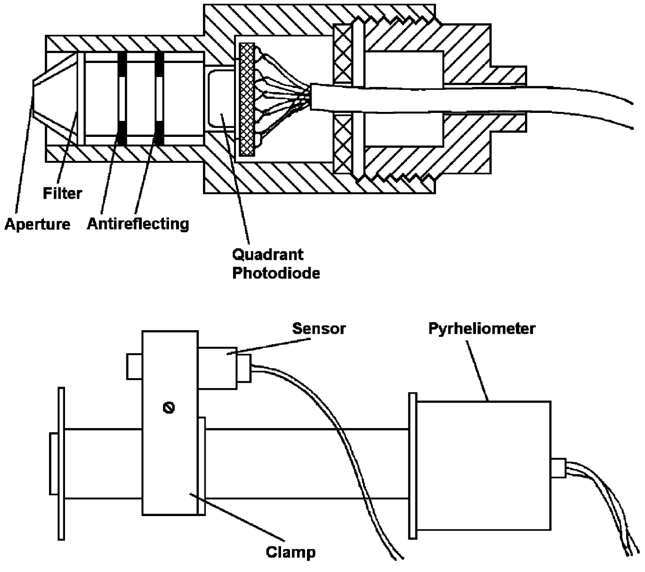

Fig. 3. Cross-section of the pyrheliometer with the sensor.

3. Action of the system

3.1. Position of the sun

The position of the sun must be established for one geographical point, where the measurement will be done. Two angles are important—the altitude and the azimuth. The system is called ALTI-AZIMUTH.

The mechanism was constructed and tested in the city of Valparaiso, Chile. The diagram in Fig. 4 shows the position of the sun on two days: December 21 (summer solstice) and June 21 (winter solstice) in the Southern Hemisphere.

There are two altitude curves in Fig. 4. They show that the sun, in summer (December 21), is at 0° at about 6:30 in the morning, has its maximum height (≈80°) about midday and about 21:00 h is at 0° again. Obviously, the curve for June 21 is similar, but the maximum is smaller (≈32°), the sunrise is later and the sunset, earlier. The curves for all other days of the year are between those mentioned above.

The azimuth is the angle which describes the sun's position from east to west. The two curves in Fig. 4 show the sun's motion in summer and in winter. Both curves have an azimuthal angle of 0° at midday. It is at a different time in summer and winter, due to the summer–winter change of time in Chile.

3.2. Motion of the axes

Fig. 5 shows the results of the motion of both axes HH and EE for the extreme days (summer and winter solstice). The velocity of HH is almost constant in summer,

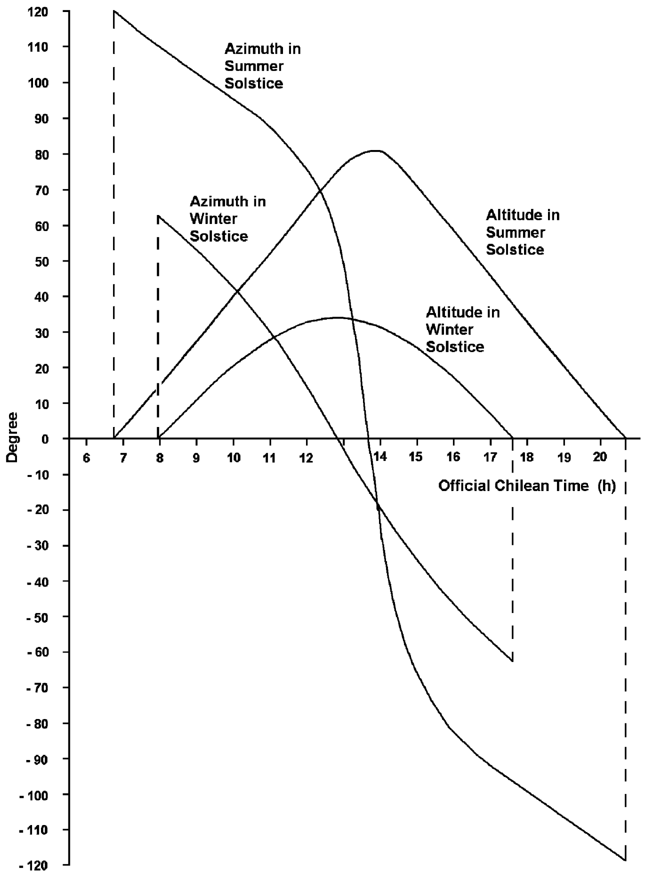

Fig. 4. Sun positions in Valparaiso in ALTI-AZIMUTH coordinates.

while there are some variations in winter. The movement of axis EE is more complicated and is in the range of about 50°. It reaches its maximum value of 120° in summer (December 21—sunrise and sunset) and its minimum of about 35° at midday on June 21 in the Chilean winter.

3.3. The four-quadrant detector

The sensor for measuring the sun position consists of a four-quadrant photodiode (Fig. 6). The diagram shows four main zones—north-east (NE), north-west (NW), south-west (SW) and south-east (SE). A beam of light illuminates a part of the four zones through an aperture (Fig. 6). When the sensor moves (or the sun's position changes), the beam illuminates different portions of each quadrant and consequently produces different currents in the diode.

An electronic circuit is used to measure the current from quadrants NE, NW, SW

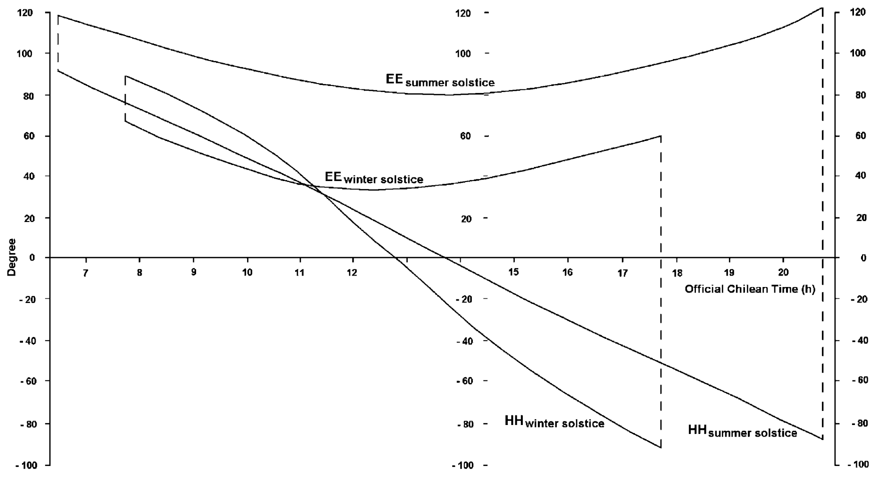

Fig. 5. Positions of axes EE and HH at summer and winter solstice in Valparaiso.

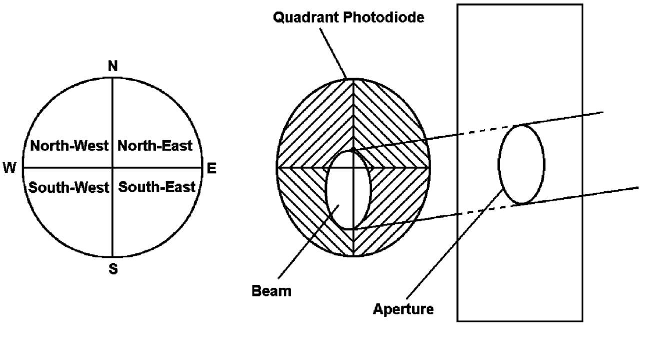

Fig. 6. Four-quadrant sensor.

and SE. Error signals for the west–east and north–south axes are obtained by properly summing and deducting the currents [4].

3.4. Strategy of control

Several functions (depending on solar irradiation and control status) are to be realized by the mechanism. After finding the sun, the system starts working in “CLOSED LOOP” mode.

Getting the transfer function is rather complicated, but it can be derived from the block diagram of Fig. 7:

$$\varphi_s = (\varphi_{s,h}, \varphi_{s,e}) \tag{1}$$

$$\varphi_m = (\varphi_{m,h}, \varphi_{m,e}) \tag{2}$$

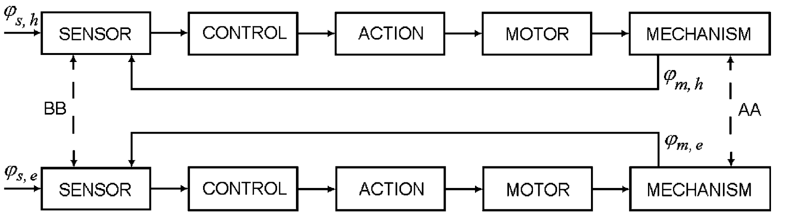

Fig. 7. Transfer functions for both axes.

where φ_s is the angle of the sun, φ_m is the direction to which the mechanism moves, subscript h is for axis HH and subscript e is for axis EE.

The cross-coupling of AA and BB is nearly zero because of the orthogonal disposition of the axes and the parallel mounting of the sensor. The angles in (1) and (2) are measured respective to an arbitrary reference.

The completed system as an automatic one is shown in Fig. 8. There are five blocks presented. Block A represents input signal processing. It receives the previous instructions, given by the operator with the aim of obtaining a given response (operation to energize the system etc.), and information coming from the phototransistor (detecting day–night) as a binary signal, the potentiometer (its level of voltage is a codification of the angle) and the two limit switches (binary). Block B presents input physical signal processing—the levels of radiation transformed into voltage by means of the sensor and the pyrheliometer. Block C represents output physical signal processing—the signals to actuate the motors and the radiation

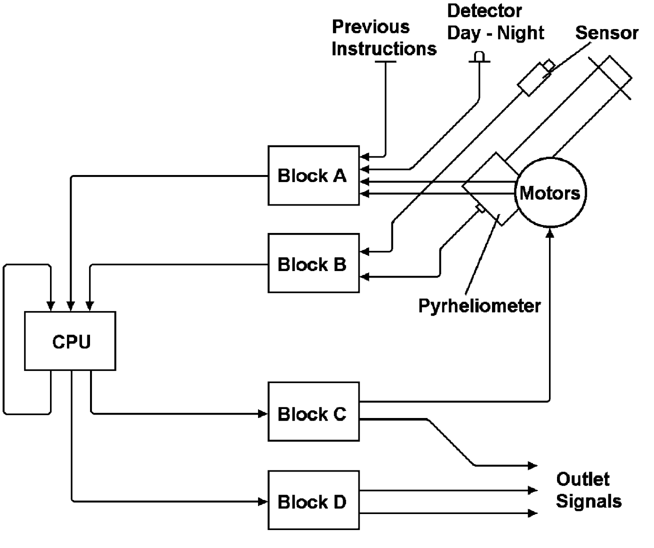

Fig. 8. Complete system as an automatic one. Block A—input signal processing, Block B—input physical signal processing, Block C—output physical signal processing, Block D—output signal processing, CPU—central processor unit.

measurement sent for registration. Block D performs the output signal processing—alarm signals and a “bit” to tell whether the outgoing measurement is valid or corresponds to the wrong operation. The central processor unit (CPU) is an old Z 80 processor, which controls the logical processing of all information, decides when the control loop must be closed or, if not, what must be done and gives information on the status of the mechanism. The different actions are shown in Table 1.

Fig. 5 shows that axis HH has an approximately constant velocity and axis EE has velocity varying between 40° and 120°. As cloudiness can occur at any moment, it is not possible to locate the EE axis without using a rather sophisticated system. The solution was to move the EE axis as a pendulum between 20° and 100° until the sun was detected. The problem with the angle difference in the extreme cases is solved by means of the cone sensor, which has a range of about 40°. The motion as pendulum is realized using the signal from the potentiometer of axis EE and applying it to a comparator with hysteresis. Axis HH needs to move at about 15°/h (180° in 12 h—1 solar day). It was realized with the motion of axis HH using pulses from an electronic clock. The required velocity can be reached if the impulse duration is varied.

4. Experiments

The system was tested in parts, simulating the conditions under which it would work. After assembling, it gave the expected results. The levels needed to establish the different statuses are not critical (for example, the level of radiation in the morning for the beginning of the SEEKING function). All regulations had some tolerance, which makes the process very easy.

It was observed that the change of state from SEEKING to AUTOMATIC was done without problems by the radiation in the preset cone. This operation could have a duration of several minutes until the pyrheliometer is again directed towards the

Table 1
Actions of the tracker

Action	Loop	Operation
EXTERNAL	OPEN	The mechanism starts acting under the influence of external signal. It is possible to govern it from the table of operation.
RETURN	OPEN	Axis HH reaches the west ($H = 0$). Subsequently, the mechanism returns to $H = 180°$ to the east. Axis EE is kept in the position reached last.
WAITING	OPEN	The mechanism waits for signals from the regulation system.
SEEKING	OPEN	The sky is clouded (or the sun is not visible). The mechanism seeks the sky till it finds the sun’s position. Axis HH moves with constant velocity and axis EE moves like a pendulum.
AUTOMATIC	CLOSED	The sun is in the visible cone of the sensor. Then the loop closes for automatic action.

sun. The reason is the slow-acting HH axis. But if axis HH is near the final position, the operation could take less than 20 s.

The regulation of the parameters requires simultaneous measurement of the radiation. It was done with the same pyrheliometer, which was directed towards the sun. Most of the regulations were done in CLOSED LOOP. A test to determine possible cross-coupling of the axes was done, but with negative results.

After adjusting the system, complete experiments were performed. An example of about two hours of pyrheliometer reading, governed by the system, is presented in Fig. 9. The system was on regime AUTOMATIC, following the sun without appreciable deviation. When the radiation decreased to less than 140 W/m^2, the measurement of the cone provoked a change from AUTOMATIC to SEEKING. This was the reason that the radiation fell to zero at about 14 h, but came back some minutes later. A little before 15 h a shadow of a building reached the instrument. This triggered SEEKING around the point where the sun disappeared.

5. Conclusions

A low-cost automatic closed-loop sun tracker was designed, built and tested. It was used to measure direct solar radiation automatically with a pyrheliometer. The velocities of the axes are relatively low, but the design of the system ensures long time working without expensive maintenance. For solar irradiation below 140 W/m^2 the registration falls suddenly to zero, but above this value the system works stably. The calculation of the transfer function is an object of future work.

It is possible to use this type of tracker with larger and heavier systems, like solar panels and concentrators. Other cheaper tracking sensors could be used. Digital (DSP) control should be used to get higher resolution and better response.

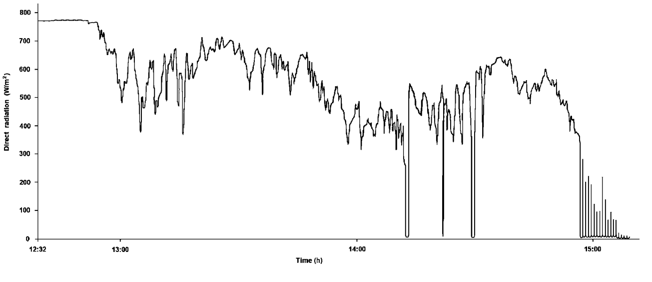

Fig. 9. Results of the pyrheliometer reading, governed by the system.

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