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Sun-tracking System Design for Parabolic Dish Solar Concentrator

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***Abstract*—A sun-tracking system design for a 3m diameter Parabolic dish Solar Concentrator is presented. The mechanical design with azimuth-altitude configuration and the developed control algorithm are exhibited. Alignment accuracy and mechanical requirements are studied. A position sensor design is presented, and a system prototype is shown.**

***Index Terms*—Sun-tracking, Parabolic dish solar concentrator, Azimuth-altitude**

I. Introduction

CONCENTRATING solar power (CSP) is a promising renewable energy source. By concentrating the sunrays in a reduced area, CSP systems can attain very high temperatures. This characteristic presents them as a suitable option not only for electricity generation, but also for industrial applications where a high temperature heat source is required.

Parabolic dish solar concentrators (PDSC) are a CSP system composed of a reflective surface shaped as a paraboloid of revolution (i.e., a parabolic dish), a support structure, a receiver and a sun-tracking system. The entire sun irradiation that impacts the parabolic dish is reflected towards its focus, where the receiver is placed. This energy concentration allows the PDSCs to achieve temperatures as high as 1500 ºC [1], [2]. They have reported the highest direct solar radiation into electricity conversion efficiency – nearly 30% [3] – when coupled with Stirling engines. State-of-the-art PDSCs have demonstrated thermal efficiencies (ratio of the heat absorbed by the heat transfer fluid to the solar energy incident on the PDSC aperture) of 70.0 – 75.7 % [3] at normalized conditions.

Mendoza Province, in Argentina, presents a great potential for CSP developing. The global solar radiation reaches a monthly average of 7.5 kWh/(m^2·day) on December [4]. It has a minimum of 2.5 kWh/(m^2·day) on July, and accounts for 1,8 MWh/m^2 on a year.

In this paper, we present the mechanical and control system design of a sun-tracking system for a 3m diameter PDSC present at CEDIAC Institute in the National University of Cuyo.

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II. Design considerations

The solar concentrator was built from a grid type parabolic antenna adapted to achieve a parabolic solar concentrator, as it can be seen on Fig. 1. Reflective aluminum stretched membranes were used to create the reflective surface. An altitude-on-azimuth rotation structure was mounted to support it. Constructive details can be found in [2].

III. System requirements

A. Support structure and sun-tracking system types

The parabolic dish axis must be held parallel to the sunrays in order to reflect them into the receiver aperture. Otherwise, the sunrays would not focus on the receiver. A two axis sun-tracking system capable of orienting the parabolic dish is thus required to compensate the apparent movement of the sun in the sky.

Several support structure and sun-tracking system designs exist. The PDSC considered in this article has an altitude-on-azimuth configuration, schematized on Fig. 2. The entire structure turns on a vertical axis (azimuth). The parabolic dish turns on a horizontal axis (altitude) which is fixed to the structure.

Fig.1. PDSC at CEDIAC Institute, Universidad Nacional de Cuyo.

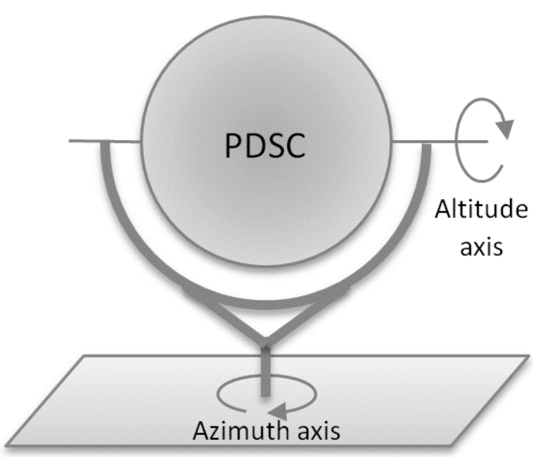

Fig. 2. Support structure configuration of the PDSC.

B. Alignment accuracy

Required alignment accuracy between the sunrays and the parabolic dish axis was calculated based on the existing PDSC dimensions: 3.01 m diameter and 0.70 m depth. The parabolic dish projected area, i.e., the circular area described by the parabolic dish contour, was approximated by a structured grid of 2 cm squares, as it can be seen on Fig. 3. One incident sunray per square was considered, with a variable misalignment in relation to the parabolic dish axis.

The focus of the dish is located on its axis at 0.80 m distance from its deepest point. The trajectory of each reflected beam was calculated in order to find its intersection with the focal plane, i.e., the plane that contains the focus and is perpendicular to the dish axis. The graphic obtained can be seen on Fig. 4.

The receiver aperture is a 0.20 m diameter circle placed on the focal plane, its center aligned with the parabolic dish axis. Thus, any reflected solar beam that reaches the focal plane at a point further than 0.10 m from the center of the receiver aperture will not be exploited. This phenomenon is illustrated in Fig. 3 and 4 assuming a 1.000 º misalignment.

TABLE I
CALCULATED ALIGNMENT EFFICIENCY

Misalignment	Number of sunrays incident on the PDSC	Number of sunrays reflected into the receiver	Alignment efficiency
0.246 º	17593	17593	100.00%
0.250 º	17593	17591	99.99%
0.300 º	17593	17512	99.54%
0.500 º	17593	16774	95.34%
0.750 º	17593	15730	89.41%
1.000 º	17593	14765	83.93%

Several misalignment values were essayed, and the alignment efficiency, i.e., percentage of the sunrays incident on the PDSC that are exploited, was calculated on each case. Some obtained values can be seen on Table I.

This method only considers the efficiency loss due to the misalignment, and assumes the reflecting surface is perfectly parabolic. The PDSC intercept factor is affected by both, misalignment and surface optical quality.

It was found that to achieve 100.00 % alignment efficiency the misalignment between the PDSC axis and the sunrays must be lower than 0.246 º. In addition, the alignment efficiency – and thus, the PDSC overall efficiency – is highly sensitive to the alignment accuracy. A misalignment of 1.00º reduces alignment efficiency to 83.93%.

It was also concluded that the alignment accuracy requirements are more relaxed when the parabolic dish is shallower.

C. Mechanical design parameters

The greatest effort the structure must resist is the one

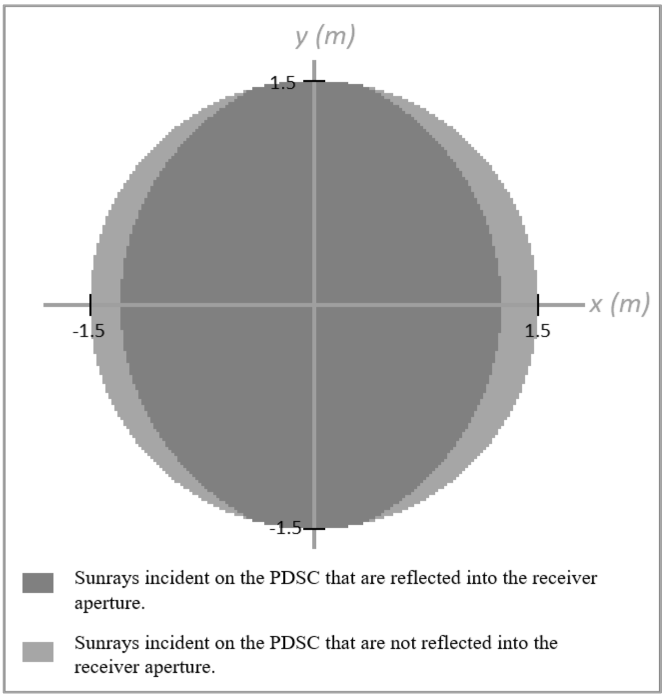

Fig. 3. Parabolic dish projected area approximated by a structured grid of 2 cm squares, seen from the perspective of the sun. Each square is colored to differentiate the exploited incident sunrays when they are misaligned 1.000º towards the positive x-axis on the x-z plane and they strike from the reader's position. The PDSC axis coincides with the z-axis.

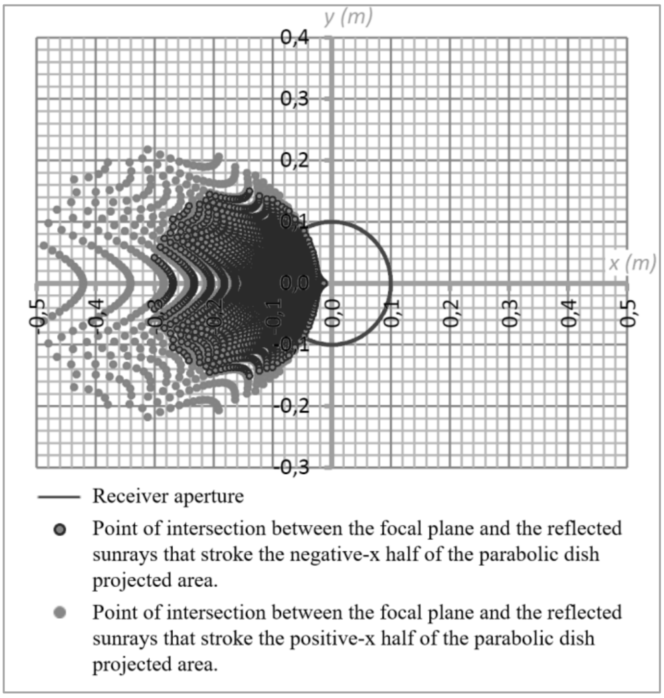

Fig. 4. Focal plane seen from the perspective of the sun. The points of impact at this plane of the reflected sunrays are represented, for the case when the incident sunrays are misaligned 1.000º towards the positive x-axis on the x-z plane and they strike from the reader's position.

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caused by the wind. In the region, a particularly strong wind phenomenon called Zonda occurs several times a year. 90 km/h wind speeds can be reached. A safe position was considered for these cases, consisting on the parabolic dish facing towards the zenith. The effort caused by the wind at this speed was calculated assuming a horizontal direction, which maximizes the bending moment on the structure. Given its dimensions, it was determined that the bending moment acting on the base of the structure is 1.593 kNm.

At working position, the wind direction was assumed parallel to the parabolic dish axis. It was determined that in these conditions the 1.593 kNm bending moment on the base is reached at a wind speed of 39.0 km/h. This was therefore defined as the limit working speed.

The base of the structure was redesigned – as it can be appreciated on Fig. 5 – and rebuilt to resist this bending moment with a safety factor of at least 2.00 on every component.

The moment of torsion acting on the dish was calculated assuming only half the dish surface is stroke by the wind with the direction of the parabolic dish axis at maximum working speed (39.0 km/h). It was determined as 0.209 kNm. This was defined as the design working torque for the sun-tracking system, i.e., the minimum torque the tracking system must produce on each axis at working position.

The same calculation method was followed to determine the moment of torsion at safe position (with a wind speed of 90 km/h). It was found to be 1.114 kNm. This was defined as the design blocking torque, i.e., the minimum torque the tracking system must be able to block on the altitude axis at safe position.

D. Angular movement amplitude

The greatest amplitude of the sun movement on both axes occurs at the summer solstice. At the PDSC location latitude – 32º 52’39’’ S – the altitude angle of the sun position reaches a maximum of 80.57º (0º being the horizon and 90º being the zenith). The azimuth angle has a range of 236.53º that day (118.26º at dusk and -118.26 º at dawn, 0º being the north). This was set as the required azimuthal amplitude for the sun-tracking system.

The altitude amplitude requirement was defined as 90º, imposed by the safe position.

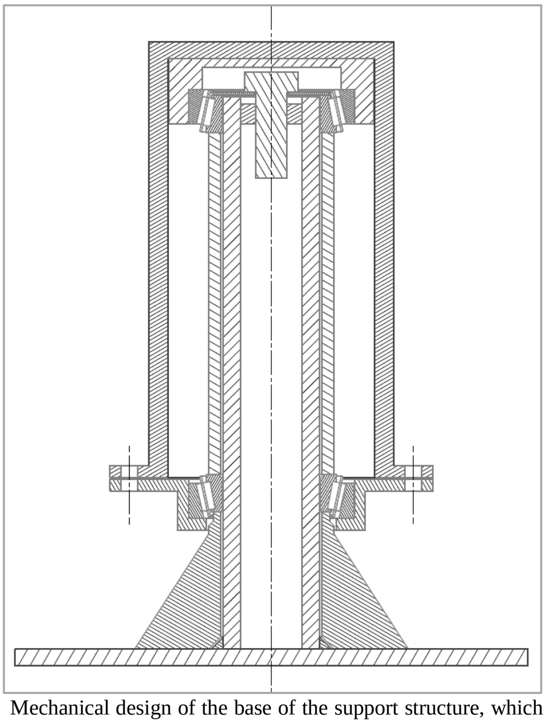

Fig. 5. Mechanical design of the base of the support structure, which allows azimuthal rotation.

IV. System design

A. Mechanical Design

Considering that the apparent movement of the sun has a very slow speed – ranging from 0.23º/min to 1.40º/min – and the high accuracy required, stepper motors where chosen to drive the system. Discrete movement of the axis with servomotors was taken into account, but too frequent start-stops of the engines would have been required, consequently diminishing the motors lifetime.

The available stepper motors are NEMA 23 of 2.45 Nm torque and 200 steps per turn, with TOSHIBA TB 6560 drivers.

Azimuthal Mechanism

A low cost Azimuthal mechanism was designed, coupling five bicycle chain drives on two fixed axes. The stepper motor is fixed to the ground and operates the first chain drive. The fifth chain drive rotates the structure on the azimuth axis. The required reduction ratio was calculated based on the design working torque (0.209 kNm). A driven/drive ratio of 498:1 was obtained. The fifth chain drive requires a dual chain, so that each crown-chain-sprocket stage has a safety factor of at least 2.20 (based on the tangential force).

Altitude Mechanism

The Altitude mechanism design can be appreciated on Fig. 6. A 1.60 m radius semi-circular guide is attached to the parabolic dish, its center coincident with the altitude axis. A bicycle chain is held to the guide and driven by a 7.5:1 worm gear reducer, which is coupled to the stepper motor. The gear reducer, and thus, the motor, is attached to the

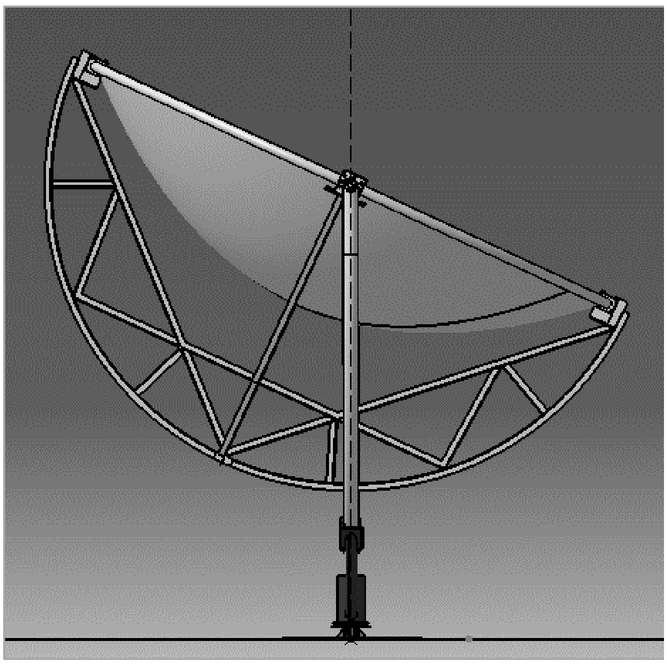

Fig. 6. Altitude mechanism design.

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turning support structure.

The semi-circular guide provides a great reduction ratio and therefore a very small tangential force on the chain. This fact allows it to easily resist both the blocking and working design torques (3.14 safety factor). A 588:1 reduction ratio was obtained. The holding torques of both the worm gear reducer and the stepper motor are not exceeded.

B. *Control System*

A closed-loop control system was designed to position the altitude and azimuthal axes of the PDSC, due to the high precision required. It includes a position sensor, two encoders, a GPS, two motor drivers, an SD card, limit switches and a wind speed sensor.

Position sensor

A sensor is necessary to survey the actual position of the PDSC regarding to the sunrays direction. Many design concepts have been presented which are based on a shade balancing principle by means of photodiodes or phototransistors [5], or by image processing [6].

Sun-pointing sensors consist of a directional element (a bar or a plaque) aligned with the parabolic dish axis and a perpendicular surface where the shadow of the former can be projected. The shadow length is proportional to the misalignment between the element (and thus, the parabolic dish axis) and the sunrays. If the element is a bar, the direction of the shadow also indicates the direction of the misalignment and image processing is used to measure both amplitude and direction. If it is a plaque, two of them are necessary to determine the direction and photodiodes or phototransistors are employed. A plaque parallel to the altitude axis will produce a shadow length proportional to the altitude angle component of the misalignment, and a plaque perpendicular to the altitude axis will produce a shadow length proportional to the azimuthal component of the misalignment.

Collimator sensors follow the same measurement mechanism, but they project a light spot or a light line instead of a shadow. They consist of a tube or chamber with an orifice (punctual or linear) on its upper surface, which is perpendicular to the parabolic dish axis. The light spot or line is projected on the lower surface of the tube, which is parallel to the upper one. The projection displacement is proportional to the misalignment. The advantage of this type of sensors is that they reject diffuse light.

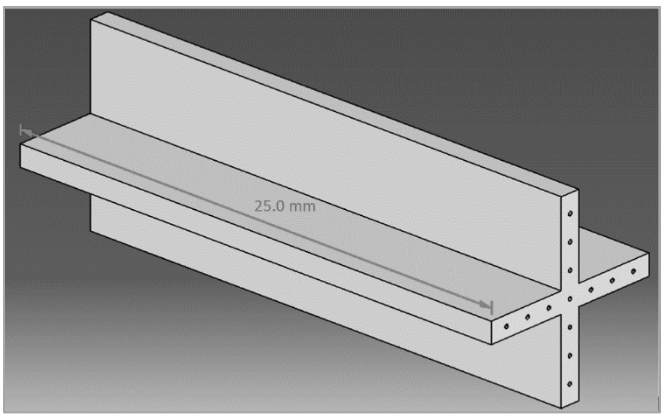

Fig. 7. PDSC position sensor design.

Tilted-mount photo sensors compare light intensity in two equally and opposed tilted surfaces in relation to the parabolic dish axis.

A position sensor was designed. It can be seen on Fig. 7. It is a collimator type sensor. A series of cylindrical orifices between two parallel cross-shaped surfaces let the sunlight pass through depending on its orientation, as it can be seen on Fig. 8. The central orifice is perpendicular to the cross-shaped surface. The ones next to it, i.e., central-middle, are tilted 0.125º towards the central orifice. The ones next to those, i.e., central-external, 0.250º; and the external ones, 0.500º. The distance between the two cross-shaped surfaces is 25.0 mm and the orifices diameter is 1.0 mm, so that a 0.250º misalignment between the sunrays and the orifice axis will completely block the light. Phototransistors are placed in each one of the orifices on the bottom surface of the sensor.

The sensor is to be placed with its central orifice aligned to the parabolic dish axis and the bottom surface facing opposite to the sun. One of the crossbars must be parallel to the altitude axis. This way, a higher conductance level on a phototransistor in this crossbar will indicate a PDSC misalignment on its altitude position. The amplitude of the misalignment will be 0.000º, 0.125º, 0.250º or 0.500º depending on if the phototransistor is the central, central-middle, external-middle, or external one, respectively. The phototransistors on the other crossbar will provide the same information about the azimuthal position of the PDSC.

Encoders

512-bit optical gray code encoders will be placed on the altitude and azimuthal axes of the PDSC to indicate their actual position. Their design was adapted from an open source model. Gear reductions will be used to match one encoder revolution to the angular movement amplitude of each axis. This provides an accuracy of 236.53º/512 = 0.462º for the azimuthal encoder and of 90.00º/512 = 0.176º for the altitude encoder.

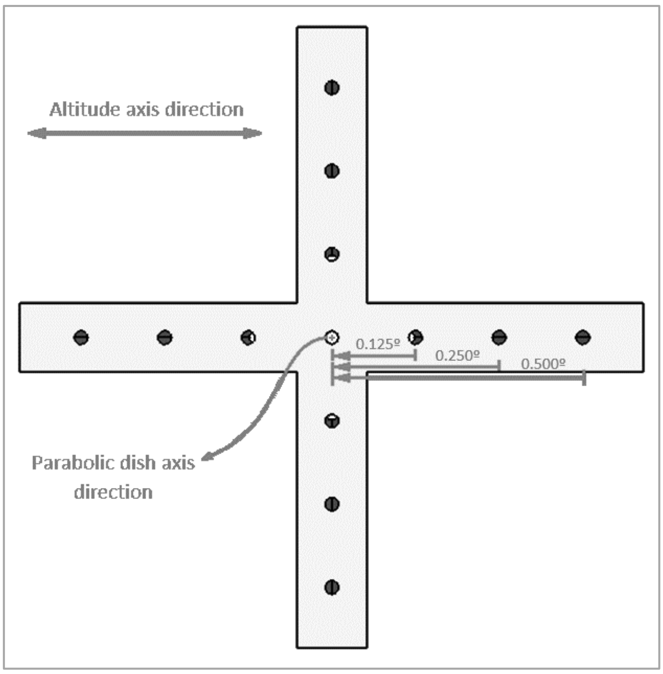

Fig. 8. Bottom view of the position sensor design. When aligned to the sun, only the central orifice is completely transparent to the sunlight.

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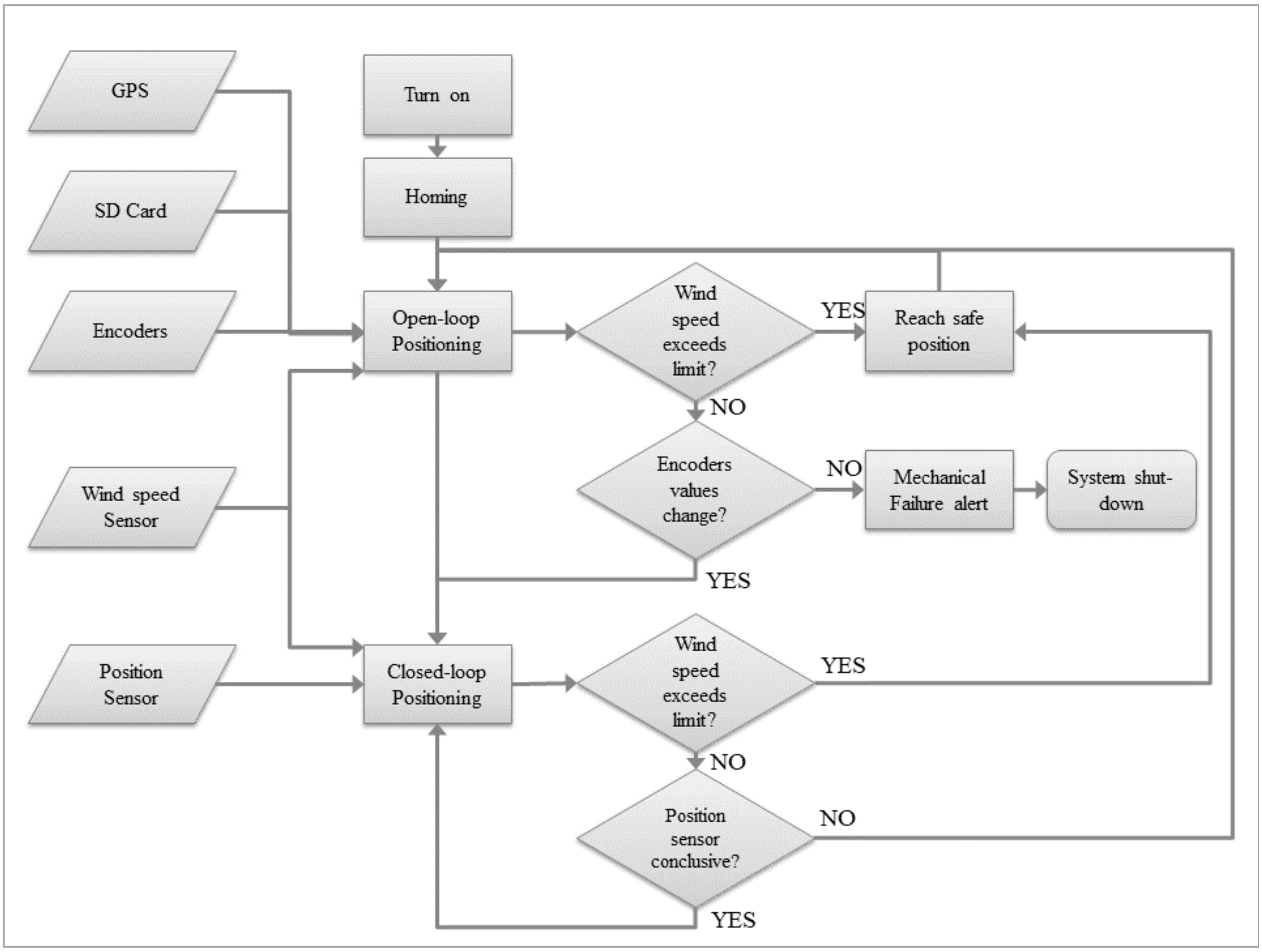

Fig. 9. Control Algorithm flowchart.

GPS

A GPS was added to obtain the time (and date) with high level of accuracy. It was preferred to an RTC to avoid calibration. It also provides a precise value of the PDSC latitude.

SD Card

The time, date and latitude values can be used to obtain the altitude and azimuthal coordinates of the sun position with the solar tracking equations, as described in [7]. In order to minimize computation time, the azimuth and altitude values where calculated with sufficient precision and stored as tables into an SD card.

Homing

Limit switches will be placed on the altitude an azimuth axes of the PDSC at their extreme positions (0º, 90º and 118.29º, -118.26º, respectively). They will provide the signal necessary to set the home position of the motors.

Wind speed sensor

A wind speed sensor will be added to register in-place the wind speed to which the PDSC is exposed.

Algorithm flowchart

The system control algorithm was developed. Its flowchart can be seen on Fig. 9.

When the system is turned on, it proceeds to the Homing process. Both axes are turned in reversed direction until their limit switches are triggered. The encoder values are read and stored in order to match the current position of each motor to the actual PDSC axes positions.

The algorithm proceeds to the Open-loop positioning. The time (date included) is read from the GPS and the SD card is consulted to obtain the altitude and azimuth current position of the sun. The number of steps each motor must give from the current position (home position in this case) to attain the sun position is calculated, based on the preset mechanical reduction ratio and the number of steps per turn. The motors are set to motion and the Mechanical Control loop is activated. The encoders are read to ensure a change in their value is produced while the motors are in motion. If it is not the case, a mechanical failure alarm is displayed and the system is shut off. The process continues until both motors have advanced the calculated number of steps. The Open-loop positioning accuracy is the one obtained from the encoders and the Homing process.

The algorithm continues to the Closed-loop positioning. The conductance levels of the position sensor phototransistors are read and the proper motor is set to move backwards or forwards in order to correct the alignment error, as it was described previously. When the conductance level of the central phototransistor becomes the highest one, the motors are stopped. The position sensor continues to be read until this condition is lost and a new alignment correction is done.

The system will stay in the Closed-loop positioning unless it is disturbed, which can occur in two cases: one, if the differences in conductance between the phototransistors are not conclusive, e.g., when a cloud blocks the sun, or two, if the wind sensor reading surpasses 39 km/h.

In the first case, the algorithm will return to the Open-loop positioning and track the sun based on the encoder readings until the position sensor data is again conclusive. At that point, he Closed-loop positioning will be resumed.

In the second case, the algorithm will set the PDSC on safe position by operating the altitude motor until the 90º limit switch is triggered. The safe position will be kept until the wind speed limit is not exceeded for a certain settable amount of time, after which, the Open-loop positioning will be resumed.

The SD card values are set so that at night (negative altitude sun position) the objective altitude angle is set as 90º, i.e., safe position.

C. System Prototype

A sun-tracking system prototype has been built to evaluate the position sensor accuracy and the overall performance of the control algorithm. It can be seen on Fig. 10. An altitude-on-azimuth 10 cm structure was 3D-printed. Two small 0.18 º per step stepper gearbox motors (200 steps per revolution with 10:1 reduction ratio) where mounted on the prototype structure.

The position sensor will be installed on the prototype to test it under real sun irradiation. The number of steps will be counted until a distinguishable change in conductance value is produced.

The azimuthal and altitude mechanisms are under construction.

V. Conclusion

The sun-tracking system is a fundamental component of the Parabolic Dish Solar Concentrators. Its performance affects greatly the PDSC efficiency.

A complete azimuth-altitude sun-tracking system design – mechanical and control – was presented, as well as the accomplished constructive stages.

It was found that to achieve a reasonable alignment efficiency of 95.34 % the misalignment between the studied PDSC axis and the sunrays must be lower than 0.500 º. Shallower parabolic dishes require less alignment accuracy.

It was possible to design a low cost Azimuthal mechanism, coupling five bicycle chain drives on two fixed axes.

A robust and simple altitude mechanism was designed, which comprises a 1.6 m radius arc coupled by a bicycle chain to a worm gear reducer – capable of blocking the axis against the wind.

A closed-loop control system was designed to position the altitude and azimuthal axes of the PDSC, which meets the requirements of high accuracy and protection against high wind speed or mechanical failures.

A new collimator position sensor was designed, suitable for the considered PDSC.

The overall performance of the system will be evaluated in future works.

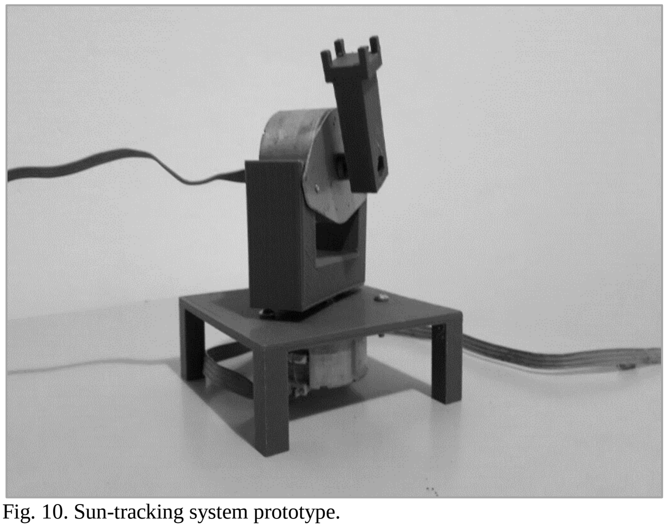

Fig. 10. Sun-tracking system prototype.

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