Optical Sensors For Solar Pointing

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Abstract

A simple, efficient and low-cost sun tracking method is presented: it is based on optical pointers used as "sun finders" and on a double guiding system. A passive tracker provides the preliminary orientation, then an active system with the sun finder realizes fine positioning and adjustments. Two optical sensors for solar pointing are proposed discussing working principle and applications. The two-axis pointer is appropriate for solar concentrators coupled to optical fibers or tiny photovoltaic cells; while the one-axis sensor is suitable for linear tracking collectors. They can be adapted to every specific application and to every solar collection device. The sensors were optically characterized indoor, under controlled and reproducible conditions, and outdoor in real working situations.

Keywords: *sun finder, optical sensor, solar energy, optical test, sun concentrator.*

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1. Introduction

A device based on the concentration of sunlight needs to track the sun in its movement in order to improve the system performance (Armstrong and Hurley, 2005; Lee et al., 2009; Mousazadeh et al., 2009). Solar systems based on light concentration require the use of an optical pointer because they can work only with direct sunlight. In Concentrating Photovoltaic (CPV) systems the primary optics is a Fresnel lens or a parabolic concentrator and a secondary optics can be added to improve pointing precision and plant collection efficiency (Altera Technical Staff, 2009; Chong and Wong, 2009). The required pointing precision is higher than the tenth of degree, which is not obtainable by passive trackers, based on the ephemerides of the year (Chen et al, 2006; Huang et al., 2009). The reasons are plant orientation problems, difficulties in keeping a high mechanical stability, wind action and high precision required by the concentrator type. Hence the solar plants employ an active tracker, based on a device that supplies to the moving system the information to correct the concentrators' orientation to maintain the alignment (Mohammad and Karim, 2012; Roth et al., 2004; Sadyrbayev et al., 2013). These devices utilized to provide the error signal to the control electronics, are commonly called "sun finders" (Bopp, 2014; Salawu and Oduyemi, 1986).

A tracking technique, based on optical sensors used as "sun finders", is discussed with a specific attention to practical realization and application of the solar pointers. The proposed strategy for sun tracking includes a double guiding system that uses two complementary procedures. The first one provides the preliminary orientation, then the second realizes the fine positioning and adjustments. The first tracking system is of passive type and it drives the motors to correctly orient the collector every day of the year. The second tracker is of active type and it employs an optical pointing system. The passive preliminary orientation is necessary to track the sun position when the solar light does not reach the pointer (in case of cloud passage or sun absence). In this way when the sun illuminates again the pointer, the active system can take the control of the collector orientation. The advantage of the double driving technique is to confer flexibility to the tracking system, which automatically follows every weather variation in all environmental conditions. The solar pointer is the optical device constituting the active guiding system of the tracking methodology. To improve the pointing precision, it is suggested the use a device including two sections, with different Field Of View apertures (FOV), corresponding to different accuracies.

This double guiding procedure to perform solar tracking is simple and effective; the realized pointers are reliable and inexpensive. The core of the active tracking system is the solar pointer. Two types of pointing sensors are presented, illustrating working principle, components, optical characterization and validation. The two-axis sensor, with pinhole, is suitable for solar concentrators coupled to optical fibers or tiny photovoltaic (PV) cells. The one-axis pointer, with slit, is appropriate for linear tracking collectors. These pointers can be adapted to every specific application and to every solar collection device. Installation and alignment become

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more and more crucial as the tracking precision increases. In practice, first the solar collectors should be properly placed on the ground, then the pointer must be accurately mounted and oriented. If the sensor is precisely aligned with the collector, the information coming from the sun finder is useful to compensate possible errors in the placement of the solar collectors. All sensors were tested in laboratory, in a controlled and reproducible environment, to provide an optical characterization of the devices. To complete the experimentation, the pointing sensors were tested outdoor, assessing their performance in operative conditions.

During the last 15 years these pointing sensors have been experimented (Fontani et al., 2011) and applied with success in different versions in several research projects concerning thermal solar concentrators (Sansoni et al. 2011), concentrating photovoltaics (Fontani et al., 2007a), hybrid solar collection systems (Ciamberlini et al., 2003), lighting (Ciamberlini et al., 2003; Fontani el al., 2007b; Sansoni et al., 2008). As essential component of devices for solar energy exploitation, the optical sun trackers have been used to perform outdoor optical tests, to experiment collector prototypes or to develop researches in the field of sun light collection. In the past decade the CNR-INO Solar Collectors Laboratory has collaborated with the major Italian actors, private and public, in the energetic research field.

2. Sun pointers for high concentration tracking

In the last decade Concentrating Photovoltaic (CPV) systems have improved their diffusion and the related electronics and optical components have experienced great technological and scientific developments. Photovoltaic cells of the last generation require concentrations that can exceed 700 suns. Consequently the associated optical systems must have a quite high value of posterior numerical aperture and a very tiny Field Of View (FOV). These requirements impose a very high angular precision to the systems for sun tracking. For tracking sensors that guide high concentration systems the typical required resolution is at least 0.1°.

Optical solar trackers have been developed and experimented by CNR-INO since 1997, implementing mechanics, electronics and software to realize prototypes (Ciamberlini et al., 2003; Fontani et al., 2011). The proposed two-axis pointer is basically a “pinhole camera” without lenses, whose scheme is reported in Fig. 1. It performs sun tracking on two perpendicular axes.

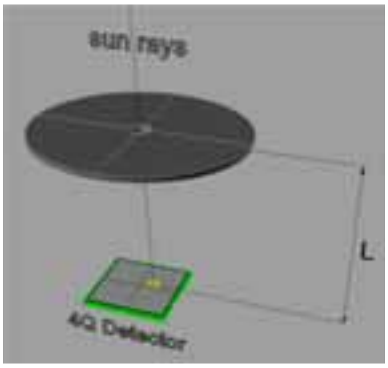

Fig. 1. A two-axis sun pointer, with pinhole.

A simplified version is represented by the one-axis pointing sensor, where the pinhole is replaced by a slit, as Fig. 2 shows. Pinhole or slit are coupled to a four quadrant photodetector. Two-axis sensors are suitable for fiber-coupled or CPV collectors. One-axis pointers are appropriate for solar troughs or linear lenses.

The working principle is illustrated in Fig. 1, which shows the main elements of the two-axis sensor: pinhole and four-quadrant detector (4Q-detector). The distance L, between pinhole and four-quadrant detector, determines the sensor Field Of View (FOV); L corresponds to the focal length of the collecting optics, hence the sun’s image moves on the photodetector with the same speed of the image on the PV cell. Sun’s image dimension and light intensity on the detector depend on the pinhole diameter *d*. The angular resolution of the sensor depends on detector dimensions, pinhole size and pinhole-detector distance. The lateral dimension s of the square photodetector is few millimeters.

The FOV aperture can be obtained as:

$$FOV = 2\,\mathrm{arctg}\frac{s}{2*L} \qquad \text{(eq. 1)}$$

For L = 50 mm and s = 5 mm, the total FOV aperture results 5.7°.

The one-axis pointer, in Fig. 2, is analogous to the two-axis sensor, but it mounts a slit over the photodetector. Consequently the four-quadrant detector can be substituted by a 2Q-detector.

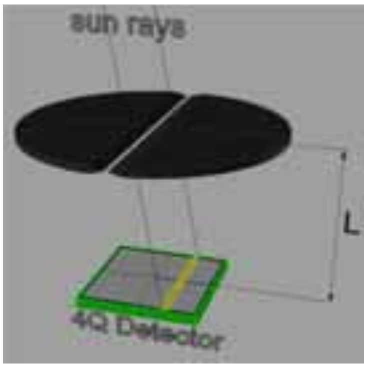

Fig. 2. A one-axis sun pointer, with slit.

3. Components and construction of the sensors

Detection configuration and light collection geometry were theoretically studied using ray tracing simulations, in particular referring to real solar plants involved in the CNR-INO research, briefly summarized in Section 1. Most of the detection geometries were obtained from ray tracing analyses of test prototypes or solar plants under development. The sensor realization evolved, customizing the pointer geometry and creating new detector typologies, on the basis of the experience in component production or driven by the extensive experimentation on the pointers.

Several versions of the described sun pointers were realized, optically characterized and practically applied on test installations and solar plants developed during 15 years of scientific experimental work (Ciamberlini et al., 2003; Fontani et al., 2007a, 2007b, 2011; Sansoni et al., 2008, 2011). Two-axis and one-axis sensors were implemented starting from the optical design, optimized in the study phase; and then suitable mechanics and electronics were developed. Two examples of two-axis pointer, with pinhole, are presented in Figures 3 and 4, showing the interior components.

Fig. 3. A two-axis sensor with narrow FOV and elevated precision.

Every sensor was previously tested in laboratory, in particular analyzing angular resolution and Field Of View aperture and then experimented in outdoor installations, testing functionality, performance and reliability. The optical characterization of the devices, performed indoor and outdoor, is summarized in Section 4, which also includes a validation by theoretical simulations; finally the assessment of the Field of View of the pointer is presented in Section 5.

Fig. 4. A two-axis sensor with large FOV.

The distance *L* can be adjusted, changing the FOV, to obtain the required precision. Figure 3 reports a version with elevated precision: *L* is 42 mm, so for detector side s = 5 mm the FOV is 7°. Figure 4 shows a two-axis sensor with *L* = 7 mm, whose FOV is 40° that corresponds to a lower precision with respect to the sun pointer in Fig. 3.

The dimensions of the four-quadrant detector was experimentally determined: typical values are 5 mm of squared detector side. The pinhole dimension depends on sensor and electronics and it was also experimentally defined. At the base of each well, forming the camera, there is a board mounting the four-quadrant detectors and their pre-amplifiers with gain adjustments.

As the sun pointer precision improves, the phases of sensor assembly and mounting on the solar collection plant become more critical: in particular it is essential to correctly and precisely place the detectors. Then the pointer must be mounted on the solar installation with the axis aligned to the collector axis. Sometimes the sensors are used in combination: for safety the solar pointer can contain two sections with different FOVs; the two sections are used in sequence, improving the precision, from the wide-angle section (low-precision section) to the narrow-angle section (high-precision section) (Sansoni et al., 2008).

The electronic system controlling the motor guide is of digital type. It employs an Input/Output DAQ device NI USB-6009 supplied by National Instrument. The I/O card is linked to a personal computer through a connection of USB type. The analogical inputs of the card are used to manage the photodetector with 2 or 4 quadrants of the solar pointer. The digital outputs are employed to guide the drivers of electric motors, which move the concentrators or the collectors' supports.

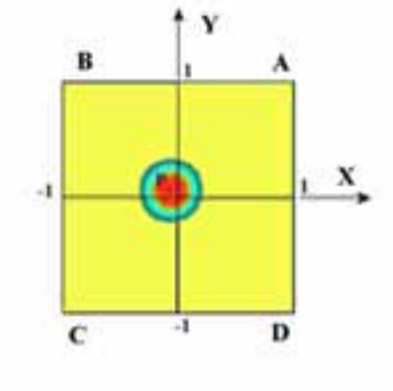

Fig. 5. Solar image on the four quadrant detector.

The position of the luminous spot is expressed by the coordinates of point P(P_x;P_y), which is the barycenter of the solar image projected by the pinhole. P_x and P_y are the coordinates with respect to the reference axes of the detector surface (X;Y), indicated in Fig. 5. For the two-axis pointer they are:

$$P_X = \frac{(V_A + V_D) - (V_B + V_C)}{V_A + V_B + V_C + V_D} \qquad \text{(eq. 2)}$$

$$P_Y = \frac{(V_A + V_B) - (V_C + V_D)}{V_A + V_B + V_C + V_D} \qquad \text{(eq. 3)}$$

where V_A, V_B, V_C, V_D are the values (in Volts) of the output signals arriving from the four preamplifiers.

The elaboration procedure is analogous for the case of one-axis pointer, but considering only a single coordinate P_x .

4. Indoor and outdoor tests of the sensors

The sun pointers were optically characterized indoor and outdoor, preliminarily in laboratory with reproducible tests and successively with real measurements in direct exposure to the sun. This solar tracking methodology is based on an optical pointing system exploiting a two-axis sensor (or a one-axis sensor) as "sun finder". The two-axis sensor contains a photodetector coupled to a pinhole, while in the one-axis sensor it is coupled to a slit.

Suitable mechanics and electronics were realized for the prototypes of both pointers and to perform their optical characterization. The laboratory setup to test two-axis and one-axis sensors is illustrated in Fig. 6. A He-Ne laser beam is expanded to obtain a collimated beam. This light impinges on the pointer under test with different angles of incidence obtained by rotating the sensor. This experimentation has two purposes: the first is to test the angular sensitivity of the sun pointer; the second is to check the output voltage level. This latter must be sufficiently high with respect to the noise of the electronics; but at the same time the voltage level must guarantee a sufficient dynamic of the sensor.

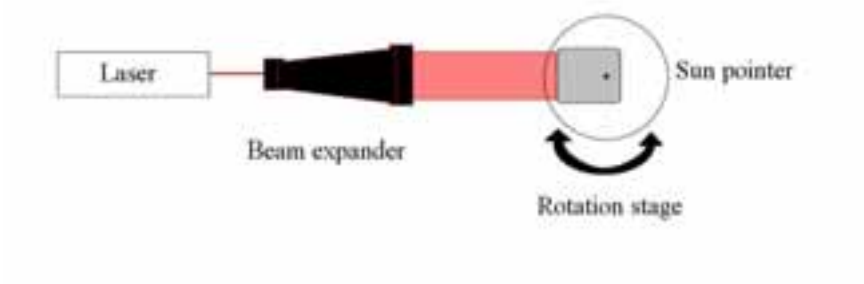

Fig. 6. Optical system to tests the sun pointer in laboratory.

Afterward the sun tracking sensors were experimented with direct solar exposure, replicating the real installation in a solar plant. In these outdoor tests the optical tracking system was applied to different testing devices for sunlight collection: solar concentrators coupled to photovoltaic cells, optical fibers or linear metal pipes. To experiment the practical functionality and to measure the sensitivity of the solar pointers the technique described in Section 1 was simplified. Instead of employing the double guiding system the solar tracker used only a driving system of dynamic type based on the optical pointer.

Some exemplificative results of laboratory measurements and field experimentation on both sensors are presented in Figures 7-9. The plots report the position of the luminous spot on the detector versus angle of incidence of solar light: each measurement represents a characterization of the optical behavior of a sun pointer. Figures 7 and 8 compare the measurements performed in laboratory with the characterization obtained with direct exposure to the sun: Fig. 7 for two-axis pointer, with pinhole; Fig. 8 for one-axis pointer, with slit. Then Figure 9 reports the field measurements for both pointers: the comparison evidences a different slope of the curves that corresponds to a different sensitivity.

The two-axis sun pointer is the most precise one and it executes sun tracking in two directions achieving a very high sensitivity. It performs a sun tracking with an angular precision of 0.1° or higher. It is indicated for solar optical systems requiring high pointing precision, like collectors coupled to small PV cells or optical fibers, with dimensions (diameter/side) of few mm and sometimes inferior to 1 mm.

The one-axis sun pointer reaches the same precision of the two-axis pointer but only in one direction. Hence it can be applied to linear concentrators (like solar parabolic troughs or linear Fresnel lenses), in solar thermal plants or low concentration CPV systems.

The solar tracking system is effective and precise, mainly due to the simplicity of working principle and optical components. The sensors, which can be implemented with low costs, are reliable and adaptable to every solar plant. In case of sun shading or temporary sun absence, the control program provides a realignment of the collector in few seconds. The system is able to compensate possible errors in the positioning of the device, which should be correctly aligned to the Earth axis. The described optical pointers can track the sun's position with an angular precision of 0.1°, which is sufficient for the majority of solar plant.

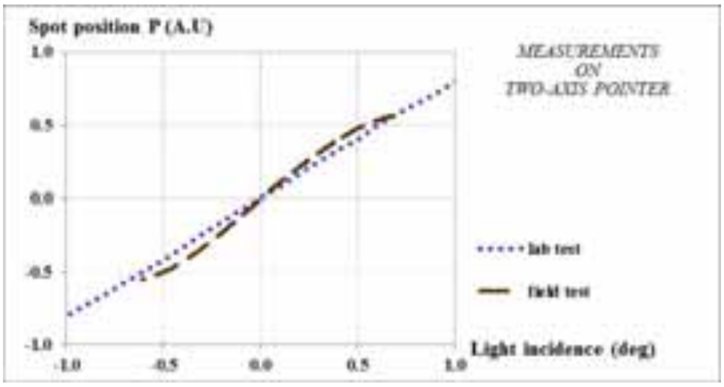

Fig. 7. Optical characterization of the sensor with pinhole.

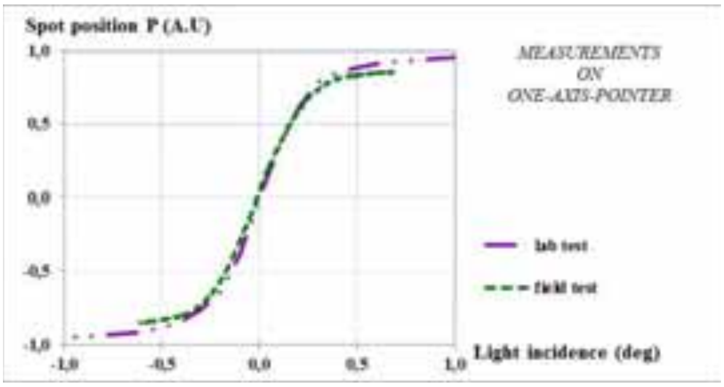

Fig. 8. Optical characterization of the sensor with slit.

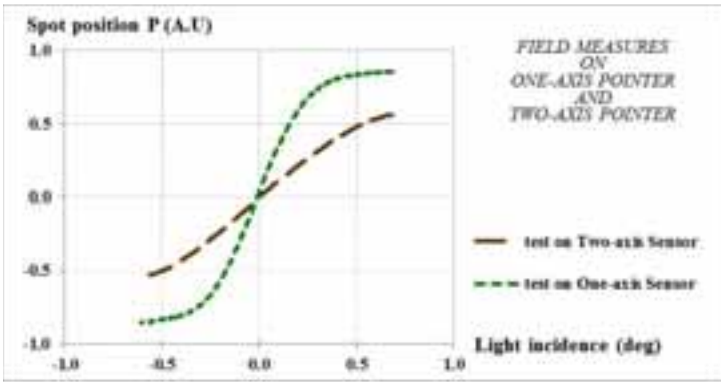

Fig. 9. Optical characterization of the sun pointers.

The validation of these experimental measurements was obtained by comparing the curves of Figures 7-9 with the theoretical data. For the curves in Fig. 7, the two-axis sun pointer was reproduced in a Zemax-EE optical simulation and the output signal was compared to the signal measured in indoor and outdoor tests. For the two-axis pointer, Figure 10 presents the comparison between the spot positions P obtained in the Zemax-EE simulation and corresponding values measured in the outdoor test. The position of the luminous spot projected on the detector is reported as a function of the incidence angle of the sunlight. The simulated curve is in fairly good agreement with the data measured in the field test.

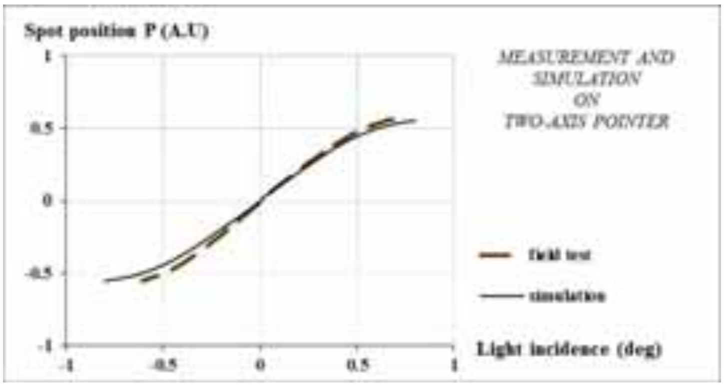

Fig. 10. Validation by ray tracing simulations for the two-axis pointer.

Each different realized sensor was examined indoor and experimented outdoor in order to assess detection characteristics and sun tracking precision. The optical characterization curves in Figures 7-9 were used to determine the zone of linear behavior of the pointers: this curve mathematically describes the working principle of each sensor and indicates its sensitivity. The validation in Fig. 10 confirms the accuracy of the experimental curves.

5. Measurement of the field of view of the sensors

Another fundamental parameter in the application of the pointers is the Field of View (FOV) aperture. The maximum sensitivity is obtained in the central part of the detector, while the total FOV aperture shows the extent of the range of operation of the sensor. The FOV aperture is obviously connected to the time in which the pointer is capable to re-track the sun in case of cloud passage or momentary absence of sunlight. The re-tracking time can be extended by using multiple sections with different FOV apertures or combining the active tracker with the passive tracker, based on the ephemerides of the year (discussed in Section 1).

Using the same set-up described in Fig. 6 it is possible to assess in laboratory the FOV of each sensor. The averaged data of these measurements are reported in Fig. 11: referring to Fig. 5, the plotted function is still the spot position P(Px;Py), given by Eq(2) and Eq(3). In practice this curve is the extension of the curves of Figures 7-9.

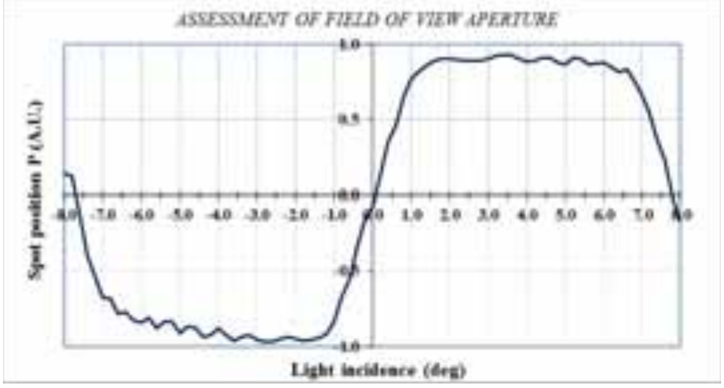

Fig. 11. Averaged measurements of the spot position P.

The spot position P remains approximately at the value of +1 (or -1) from the final angle of the linear zone to the edge of the detector. The measurement has been specifically carried from one detector border to the opposite one, even though usually the detector is mainly used in its central part. In the two lateral zones there is no more linearity between spot position P and angle of incidence, so the misalignment cannot be determined but it is however possible to try a re-alignment because the direction of the sun (in terms of up-down, left-right) is roughly known. Therefore it is useful to know the angular range within which the angular sensor still gives a valid signal in order to use it more completely. Figure 12 illustrates the two zones on the detector area: in the central zone (green in Fig. 12) P linearly depends on the incidence angle; while in the lateral zone (yellow in Fig. 12) P oscillates around +1 (or -1), and finally at the detector border the P value approaches 0.

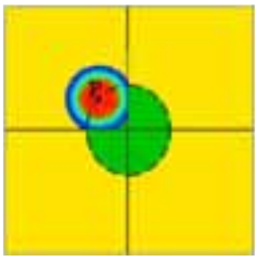

Fig. 12. Averaged measurements of the spot position P.

The determination of the FOV aperture is simply obtained from the complete plot of P values measured scanning the detector from one edge to the opposite one. In the example of Fig. 11, where the data are averaged on the measurements performed on a series of one-axis pointers, it is possible to use the sensor in a range between ± 7.5 degrees. Hence the total Field Of View aperture results 15 degrees. It is useful to remind that the FOV angle depends on the distance *L* between pinhole (or slit) and detector, which is chosen during the mounting of the device. Figures 3 and 4 show two pointers with different FOV: longer *L* gives narrower FOV and corresponds to higher angular precision (Fig. 3).

6. Conclusion

The proposed strategy for sun tracking includes a double guiding system that uses two complementary procedures: the first one provides a preliminary orientation, then the second realizes fine positioning and adjustments. The first tracking system is of passive type and it drives the motors to correctly orient the collector every day of the year. The second one is of active type and it employs an optical "sun finder". The double guiding system maintains the alignment in case of temporary sun absence or sun shading. The pointer perform an angular sensitivity higher than 0.1°, which is acceptable for many solar plants.

Two exemplificative optical pointing systems are proposed: the two-axis pointer that tracks on two perpendicular axes and the simplified one-axis pointer that tracks only in one direction. They can be adapted to every specific application and to every solar collection device. Installation and alignment become more and more crucial as the tracking precision increases. Solar installation placement, mounting and orientation of the sun pointer should be executed with particular attention to obtain an elevated tracking precision. If the sensor is precisely aligned with the collector, the information coming from the solar pointer is useful to compensate possible errors in the collector placement.

Sun pointing in one direction is required in linear collectors, solar trough collectors and linear Fresnel lenses. If the collector axis is parallel to the North-South direction, the tracking system must follow the sun in its daily excursion and the altitude of the sun over the horizon depends on Latitude and day of the year. If the collector axis is parallel to the East-West direction, the sun should not be tracked in its daily excursion. The proposed one-axis pointer can be applied to linear collectors for solar thermal plants or low concentration CPV systems.

Sun pointing in two directions is necessary to orient every concentrator with circular symmetry. In practice the tracking systems follows the sun position, which can be decomposed into two movements of single axis tracking. The combination of the two orientation adjustments gives the two-axis tracking. The proposed two-axis pointer performs solar tracking in two perpendicular directions with high sensitivity. It is indicated for solar optical systems requiring high pointing precision, like concentrators coupled to small PV cells or optical fibers.

In synthesis these optical pointing devices work as a pinhole camera without lenses. The working principle is simple, the device is adaptable and cheap, the pointer is effective and reliable.

7. References

Armstrong, S., Hurley, W.G., 2005. Investigating the Effectiveness of Maximum Power Point Tracking for a Solar System. IEEE Xplore, I, 204-209.

Chen, Y.T., Lim, B.H., Lim, C.S., 2006. General sun tracking formula for heliostats with arbitrarily oriented axes. Solar Energy Engineering 128, 245-250.

Chong, K.K., Wong, C.W.C., 2009. General formula for on-axis sun-tracking system and its application in improving tracking accuracy of solar collector. Solar Energy 83,3, 298-305.

Ciamberlini, C., Francini, F., Longobardi, G., Piattelli, M., Sansoni, P., 2003. Solar system for the exploitation of the whole collected energy. Optics and Laser in Engineering 39,2, 233-246.

Fontani, D., Francini, F., Sansoni, P., 2007a. Optical characterisation of solar collectors. Optics and Lasers in Engineering 45, 351-359.

Fontani, D., Francini, F., Jafrancesco, D., Longobardi, G., Sansoni, P., 2007b. Optical design and development of fibre coupled compact solar collectors. Lighting Research & Technology 39,1, 17-30.

Fontani, D., Sansoni, P., Francini, F., Jafrancesco, D., Mercatelli, L., Sani, E., 2011. Pointing sensors and sun tracking techniques. International Journal of Photoenergy 2011, 806518, 1-9.

Huang, Y.J., Wu, B.C., Chen, C.Y., Chang, C.H., Kuo, T.C., 2009. Solar Tracking Fuzzy Control System Design using FPGA. Proc. WCE 2009 Newswood Limited, I, 1-5.

Lee, C-Y., Chou, P-C., Chiang, C-M., Lin, C-F., 2009. Sun Tracking Systems: A Review. Sensors 9, 3875-3890.

Mohammad, N., Karim, T., 2012. Design and Implementation of Hybrid Automatic Solar-Tracking System. Journal of Solar Energy Engineering 135,1, 011013, 1-6.

Mousazadeh, H., Keyhani, A., Javadi, A., Mobli, H., Abrinia, K., Sharifi, A., 2009. A review of principle and sun-tracking methods for maximizing solar systems output. Renewable and Sustainable Energy Reviews 13, 1800-1818.

Roth, P., Georgiev, A., Boudinov, H., 2004. Design and construction of a system for sun-tracking. Renewable Energy 29, 393-402.

Sadyrbayev, Sh.A., Bekbayev, A.B., Orynbayev, S., Kaliyev, Zh.Zh., 2013. Design and Research of Dual-Axis Solar Tracking System in Condition of Town Almaty. Middle-East Journal of Scientific Research 17,12, 1747-1751.

Salawu, R.I., Oduyemi, T.A., 1986. An electronic sun pointer and solar tracking system. Solar & Wind Technology 3,3, 215-218.

Sansoni, P., Francini, F., Fontani, D., Mercatelli, L., Jafrancesco, D., 2008. Indoor illumination by solar light collectors. Lighting Research & Technology 40,4, 323-332.

Sansoni, P., Fontani, D., Francini, F., Giannuzzi, A., Sani, E., Mercatelli, L., Jafrancesco, D., 2011. Optical collection efficiency and orientation of a solar trough medium-power plant installed in Italy. Renewable Energy 36, 2341-2347.

8. Web References

Altera Technical Staff, 2009. Build an intelligent solar tracking system with FPGAs. FPGA Sources - EETimes India: www.eetindia.co.in/ART_8800561442_1800008_TA_30679a77.HTM (Feb. 2015).

Bopp, Matthias. A collection of solar finders designs. DD1US Astro Downloads, 2014: http://www.dd1us.de/Downloads/a%20collection%20of%20solar%20finder%20designs%200v5.pdf (Feb. 2015)