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Design of an innovative and simplified polar heliostat for integration in buildings and urban environments

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Abstract

The increasing improvement of energy sustainability entails an increase in the use of heliostats in small applications for urban environments. For these applications, smaller heliostats and lower distances traveled by reflected rays are proposed, and, consequently, higher tolerances in error are allowed.

This paper describes a new simple heliostatic system suitable for small applications based on a polar heliostat which redirects the sun's rays parallel to the earth polar axis. Additionally, these solar rays can be redirected towards a desired point by means of a fixed secondary mirror.

The polar heliostat is composed of a polygon that is deformable due to the rotary movement of axis A–A′ parallel to the earth's axis. Its astronomical and mechanical principles are described in the paper. The device is quite simple and it only needs a single action for its positioning, both in elevation and in azimuth, so that it is easily implemented by an electronic controller. Moreover, it is possible to associate and control different heliostats by a single engine.

Finally, in this paper, the systematic pointing error of the polar heliostat, and its dependence on the dimensions of the device, has been analyzed, finding out that the average errors decrease as the ratio between the dimensions of the deformable polygon and the thread pitch of axis A–A′ increases. Particularly, for the dimensions of the polar heliostat presented, the average pointing error of the device proposed is $\bar{\varepsilon} = 2.96$ mrad (with a standard deviation of $\sigma_\varepsilon = 3.11$ mrad), which is acceptable for small urban applications.

Keywords: Heliostat; Building integrated heliostats; Concentration systems; Natural daylighting

1. Introduction

The increasing necessity for improving the environmental and energy sustainability of buildings has resulted in the progressive development and implementation of a higher number of architecturally integrated solar devices (Chow et al., 2013; Jelle et al., 2012; Kischkoweit-Lopin, 2002; Lamnatou et al., 2015; Li et al., 2009; Quesada et al., 2012). Among the solar technologies for buildings that have received more attention in the last 10 years, those that use sun-tracking and solar concentration should be highlighted. Thus, Chemisana (2011) presents a systematized study of these technologies applied to photovoltaic production or Building Integrated Concentrating Photovoltaics (BICPV) systems. Although references to thermal concentration integrated systems are few, their advantages are known in the fields of energy polygeneration and small distributed energy systems. Therefore, González-Pardo et al.

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(2013) analyze the integrability of small concentration systems based on heliostat fields distributed on building facades. Furthermore, Menoufi et al. (2013) prove that BICPV systems have a lower environmental impact than BIPV (Building Integrated Photovoltaic) systems because concentration allows a reduction in the number of solar cells, which are the elements with the higher environmental and economic cost (Chemisana et al., 2013; Muhammad-Sukki et al., 2014).

Natural daylight, together with energy savings and better sustainability indexes, has other advantages, including a better visual quality and color reproduction, as well as a positive influence on psychological factors (Li and Wong, 2007; Li, 2010). The need to improve the use of daylighting techniques inside buildings thus means that systems based on heliostats have been used in recent years to redirect solar light (Rosemann and Kaase, 2005; Whitehead et al., 1984; Wong et al., 2012).

Kischkoweit-Lopin (2002) shows a general review of daylighting exploitation systems where it is emphasized that systems based on heliostats are the most complex. Tsangrassoulis et al. (2005) describe a system based on the capture of direct solar illuminance by using heliostat systems and Fresnel lenses to guide it with optical fiber cables. Although the results are positive, they are constrained by the high cost of the system. As a consequence, Rosemann et al. (2008) recognize that there was no solution with demonstrated economic viability.

Therefore, the cost reduction in heliostats to be used in buildings is a necessary objective for both photovoltaic thermal and lighting applications. There is literature on this reduction in conventional central receiver thermal power plants (Blackmon, 2013; Kolb et al., 2007; Pfahl et al., 2013), but references on its use in buildings are scarce (Chen et al., 2001, 2003).

Heliostats usually proposed for these uses are smaller than heliostats implemented in central receiver thermosolar power plants. Moreover, in building applications, the distances traveled by the reflected rays are lower than in thermosolar power plants, which allow higher tolerances in directional errors of the reflected rays. Thus, for instance, the tracking error of heliostats for solar ovens is of the order of 1 mrad (Aiuchi et al., 2006), which is remarkably lower than the value of the apparent diameter of the sun (9 mrad). This value of error (1 mrad) is insignificant in urban applications as it entails a deviation of the order of centimeters in focus located at a distance of 100 m.

Finally, it should be highlighted that the heliostats found in literature, as well as those proposed by commercial undertakings specialized in this field (Heliostat.nl, Practical Solar, Inc., Solar MEMS Technologies S.L., Solenica, Egis), require two engines for their correct orientation and their own electronic controller. In contrast, in this paper, a prototype of a simple heliostatic system suitable for redirecting sun's rays towards a target point is presented. To achieve it, the system consists of two different elements: the first one is a mechanical polar heliostat which redirects the incident sun's rays parallel to the earth polar axis, and the second one is a fixed secondary mirror which redirects the rays towards the desired point.

This paper is focused on the description of the features and running of the polar heliostat, due to its complexity and innovation. This device has the advantage of having a single engine per heliostat. It also allows associations among heliostats sharing the same engine and, as a consequence, the same movement controller. Finally, in this paper, the possible pointing errors derived from these simplifications are analyzed as well as their influence on the performance of the device in small applications.

2. Description of the device

2.1. Astronomical principles of the proposed design

The direction of the incidence of the sun's rays on the earth's surface depends on the relative position between the earth and the sun, which, at the same time, is conditioned by the translation and rotation of the earth. To represent the direction of the rays, the sun vector, $\vec{s}$ is commonly used because it is defined as a unitary vector in the direction of the sun's rays (Sproul, 2007). Fig. 1 shows the sun vector on an equatorial reference system with the origin in the center of the earth, the OXY plane coinciding with the plane of the equator so that the OZ axis is parallel to the earth's rotational axis, and the OZY plane coinciding with the plane of the local meridian.

Considering that the earth's rotational axis is inclined with respect to the ecliptical plane, the angle formed by the sun's rays – called declination (δ) – changes throughout the year. Several authors have proposed mathematical models to calculate declination, assuming that it only depends on the Julian day. In this context, attention should be drawn to Spencer's model (Spencer, 1971), with an error

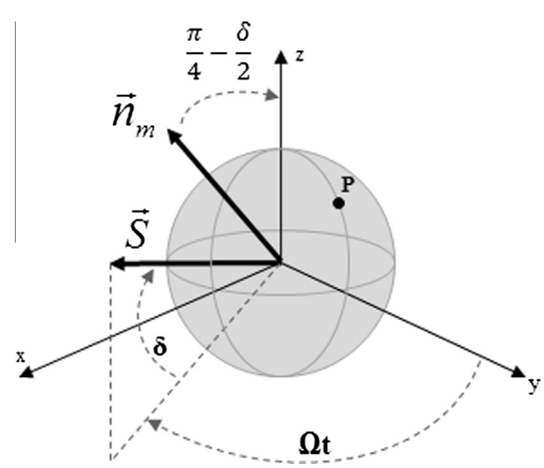

Fig. 1. Relevant vectors in the design of the proposed heliostat in an equatorial reference system (with the origin O in the center of the earth, the OXY plane coinciding with the plane of the equator and the OZY plane coinciding with the plane of the local meridian).