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Assessment of the pointing error of heliostats with a single not polar rotation axis for urban applications

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A B S T R A C T

Electric lighting is the most important source of power consumption in buildings. For that reason, one of the most common measures adopted when constructing sustainable buildings is the use of elements of daylighting to reduce the use of artificial lighting. However, high density of buildings in cities complicates the introduction of natural lighting in buildings, being necessary to resort to concentration and tracking devices, such as heliostats.

One of the most important limitations of heliostats for urban applications is that, when using a polar heliostat, like the Fahrenheit one, its location is determined by the direction of the Earth's rotation axis and the point toward radiation needs to be redirected. However, this location may not be available due to architectural restrictions.

In this paper, the behavior of this kind of heliostat as a generic one, whose axis does not need to be oriented along the direction of the polar axis, has been studied. It has been found out that it is possible to define a direction around the heliostat must rotate in order to reflect sunbeams toward the desired point with high precision. Additionally, the pointing errors of the device proposed have been analyzed. Considering that the lengths traveled by reflected sunbeams in urban applications are of about tens of meters, the errors estimated (0.01 rad average pointing error) are assumable since they would entail absolute errors of the order of centimeters.

1. Introduction

The Climate Conference recently held in Paris has concluded with the commitment of the representatives of the 195 participating countries to limit the rise in average global temperatures to below 2 °C. To this end, among other proposals, it fosters the need for promoting energy efficiency as a measure to decrease the consumption of non-renewable energies and to reduce greenhouse gases emissions.

In this respect, one of the key sectors to promote energy efficiency measures is lighting. Power consumption for electric lighting at a global level (OECD) accounts for 15% (Han and Kim, 2010) and, far from shrinking, it continues increasing. As a matter of fact, the consumption of electric power for lighting increases annually up to 0.7% (Ullah and Shin, 2014).

In cities, besides street lighting, buildings are one of the elements with a higher consumption due to lighting. In fact, electric lighting is the most important source of power consumption in buildings (Ullah and Shin, 2014) since from 40% to 50% of their power consumption goes to electric lighting (U.S. Green Building Council, 1996). In considering the prospects, the construction of sustainable buildings is being promoted. These buildings, among other measures to improve energy efficiency, have elements of daylighting to reduce the use of artificial lighting, thus decreasing the consumption of fossil-based energies. In that sense, it has been found that sustainable buildings may reduce the power consumption for lighting from 50% to 80% (U.S. Green Building Council, 1995). Furthermore, the use of natural lighting elements in buildings reduces the economic costs for the inhabitants of the dwellings, as well as it creates a more comfortable environment and entails remarkable benefits in health and productivity (Nicolow, 2004; Boubekri, 2007; Kim and Kim, 2010).

The high density of buildings in cities, however, complicates the introduction of natural lighting in buildings. To solve it, it is frequent to resort to concentration, in order to increase the energy by surface unit, and tracking, so that the collectors keep the optimal orientation to achieve the maximum collection. As a consequence, there has been recently an increase in the demand of natural lighting elements for buildings by architects, which has favored the research and their technical development (Tsangrassoulis et al., 2005). Several authors Kim and Kim (2010)

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and Mayhoub (2014) present a deep review of the different systems of natural lighting developed in recent times, from the perspective of the theoretical bases as well as the commercial products available.

Among these natural lighting devices for buildings and urban environments, the most complex elements are those based on heliostats (Kischkoweit-Lopin, 2002). Heliostats have a system of mirrors and solar tracking that redirects solar radiation to any desired point, avoiding the physical limitations of buildings, such as shadows and orientation (Han and Kim, 2010). In this way, heliostats may be used as natural lighting elements by themselves or as a complement to other devices, like light pipes, enabling a higher collection of solar radiation quantity in their openings.

Concerning the lighting in the interior of buildings, Ullah and Shin (2012) suggest a natural lighting system combining a field of circular heliostats with a light pipe to capture, guide and distribute daylighting at the interior of a multi-floor office building. Additionally, Tsangrassoulis et al. (2005) design a natural lighting system based on heliostats, Fresnel lenses and optical fiber and González-Pardo et al., 2013 propose a vertical heliostat field integrated in the façade of the building as an active power generator and analyze its behavior regarding sun protection, passive refrigeration and natural lighting (González-Pardo et al., 2014).

Furthermore, high-latitude cities or cities located at deep valleys that may not reach adequate levels of natural lighting, such as Rjukan (Norway), have resorted to a heliostatic system that reflects solar radiation toward a specific place of the city (for example, the Town Hall Square). This solution provides simultaneously with natural lighting and meeting points for the citizens.

Consequently, in the last decades, heliostats for small urban applications are being developed to improve energy efficiency in buildings and cities. In these heliostats, considering that the distances covered by the reflected beams are more limited, admissible pointing errors are higher to those of the heliostat fields at thermosolar plants. The cost of heliostats, however, is high due to their complexity. As a consequence, there are no feasible commercial solutions from an economical perspective (Rosemann et al., 2008) and it is necessary to research on this technology in order to reduce the costs without decreasing accuracy.

In this line of work, the authors suggested in a previous work (Torres-Roldán et al. (2015)) a polar heliostat for small urban applications with an average pointing error of 2.96 mrad, which, as previously mentioned, is an acceptable error for small urban applications. The suggested heliostat, unlike other commercial products, is fit both in elevation and azimuth with a single engine. This simplifies the control mechanism and, consequently, reduces the economic cost of the device. Additionally, it is possible to combine several heliostats, controlling all of them with a single common engine.

In the proposed configuration, the axis of the heliostat must be parallel to the polar axis of the Earth. This way, the position of the heliostat is determined by the direction of this axis and the point toward which radiation needs to be redirected. Nevertheless, due to architectural limitations, the installation of the heliostat at this location is not always possible. Regarding these circumstances, this paper aims to analyze the behavior and pointing errors of the heliostat proposed by Torres-Roldán et al. (2015) when its rotation axis is not parallel to the Earth's polar axis.

2. Characterization of the proposed mode of functioning

2.1. Astronomical principles of the proposed device

To determine the movement of the device, as Torres-Roldán et al. (2015) point out, it is necessary to know at each instant of time the direction of the solar vector, $\vec{s}$, which is defined as a unitary vector in the direction of sunbeams (Sproul, 2007). Fig. 1 shows the solar vector in an equatorial reference system, where the system origin O is located at the center of the Earth, the Oxy plane coincides with the equatorial plane (consequently, the Oz axis is parallel to the Earth's rotation axis) and the Ozy plane coincides with the meridian plane of the place. The angle formed by the solar vector and the equatorial plane, resulting from the translation movement of the Earth around the Sun and the rotation movement of the Earth about its own axis, which is inclined with respect to the ecliptic plane, is known as declination, δ. Declination varies throughout the year depending on the Julian day, d_j, being zero when the solar vector is located at the equatorial plane. Several authors have proposed mathematical models to describe this angle, among which Spencer's model (1971) must be highlighted. With an error below to 1/20° (Vera, 2005), Spencer's model is calculated by means of Eq. (1)

$$\delta\,(\text{rad}) = [0.006918 - 0.399912\cos(\Gamma) + 0.070257\sin(\Gamma) - 0.006758\cos(2\Gamma) + 0.000907\sin(2\Gamma) - 0.002697\cos(3\Gamma) + 0.00148\sin(3\Gamma)] \quad (1)$$

where the daily angle Γ depends on the Julian day according to Eq. (2)

$$\Gamma\,(\text{rad}) = \frac{2\pi(d_j - 1)}{365}. \quad (2)$$

Furthermore, the angle formed by the projection of the solar vector in the equatorial plane (Oxy) and the Oy axis is called hour angle, and is consequence of the Earth rotation movement around the Oz axis. The hour angle will be given by the product of the rotation speed, considered as a constant ($\Omega = 2\pi/24$ rad/h), and the time elapsed from the solar midday, when the hour angle is null.

According to the mentioned above, the solar vector in the equatorial reference system is given by Eq. (3), where $\vec{u}_x$, $\vec{u}_y$ and $\vec{u}_z$ are the unitary vectors.

$$\vec{s} = \cos\delta\sin\Omega t\,\vec{u}_x + \cos\delta\cos\Omega t\,\vec{u}_y + \sin\delta\,\vec{u}_z \quad (3)$$

From this equatorial reference system, in order to explain the fundamentals of the device analyzed here, it is necessary the use of a different reference system $O'x'y'z'$ centered in an observer (O') located at the Earth surface, in a point of latitude φ. In this reference system, the $O'x'y'$ plane coincides with the plane of the ***horizon***, that is, with a plane tangent to the Earth's sphere at the

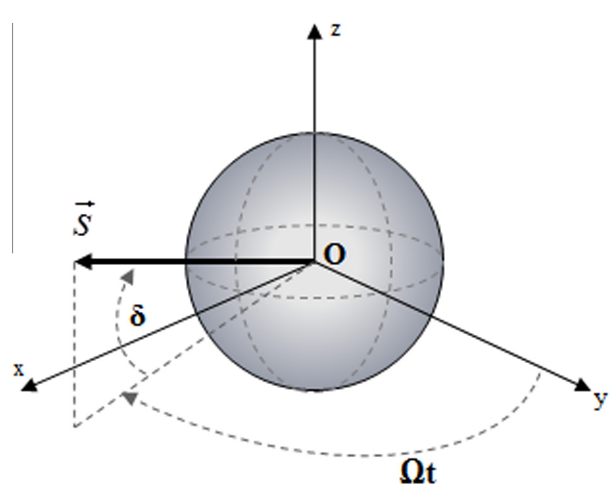

Fig. 1. Representation of the solar vector in the equatorial reference system.