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Run-time detection and correction of heliostat tracking errors

Matteo Chiesi*, Eleonora Franchi Scarselli, Roberto Guerrieri

Advanced Research Center on Electronic Systems for Information and Communication Technologies E. De Castro (ARCES), University of Bologna, Viale Carlo Pepoli 3/2, 40123, Bologna, Italy

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ABSTRACT

This paper investigates the effect of tracking errors in heliostats used in solar tower power plants and proposes an approach based on low-cost distributed electronics capable of limiting their impact. An analysis carried out through a parallel model sets the specifications for design of a closed-loop solar tracker based on a low-cost six-axis digital e-compass. A proof of concept system is devised to test the accuracy of the proposed strategy. This approach allows the solar tracker to perform a run-time detection and correction of heliostat tracking errors, with an accuracy of about 3 mrad for the azimuth angle and less than 2 mrad for the altitude angle, thus leading to a higher concentration ratio than with an open-loop solar-tracker.

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1. Introduction

The increase in energy demand coupled with the depletion of fossil fuels, has boosted interest in renewable energy and in particular solar energy, which has proven to be one of the best feasible solutions. The sun is the most abundant source of energy on earth and every year delivers more than 10.000 times the amount of energy that humans currently use [1].

From a theoretical point of view an effective way to harness solar energy on a large scale is based on solar power tower plants [2]. These systems consist of a field of highly reflective tracking-mirrors called heliostats, which focus the solar radiation upon an absorbent surface, positioned at the top of a tower. The solar radiation collected on the absorbent surface heats a fluid which is used in thermal or thermoelectric processes.

High pointing accuracy is required in order to concentrate the greatest amount of solar radiation possible. Recently, in order to become competitive with conventional electricity generation systems, solar-hybrid power plants have been studied, exploiting the Brayton cycle to increase the efficiency of the energy conversion process [3]. By heating pressurized air, the solar heat can be directly fed into the gas turbine without the loss of an additional exchanger. Furthermore these plants do not require water for cooling. The efficiency of the Brayton cycle depends on the gradient between the atmospheric temperature and the temperature of the gas turbine. Hence, Brayton turbines use receiver cavities which are smaller in aperture than those used in other plants in order to minimize convectional losses. In solar hybrid power plants heliostats thus need to be controlled even more accurately than in other plants, to avoid spillage losses and achieve a very high concentration of radiation at the receiver.

The heliostat field is one of the highest cost of the plant [4]; It represents around 50% of the initial capital investment [5] and its annual energy losses are around 47% of the total losses [6]. Several sources of error may arise within the heliostat field, inducing a poor energy concentration ratio. Nowadays some of these (such as the mechanical installation tolerance, the wind load, etc.) can be compensated by introducing a smart control system which supports distributed sensing leading to a higher concentration ratio and a cost saving due to the possibility of using mechanical systems of low accuracy [7].

The need for distributed local controllers allowing independent tracking of each heliostat and providing high tracking accuracy at low-cost, has already been recognized [8]. The open challenge is to find an effective way to runtime adjust all heliostats while keeping tracking errors as low as possible.

In this framework, this paper focuses on tracking errors that may arise in heliostat fields for solar power tower plants. In

* Corresponding author.
E-mail address: matteo.chiesi@unibo.it (M. Chiesi).

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addition, it proposes a low-cost distributed run-time control system which detects and corrects these errors. The proposed approach is supported by an analysis of tracking errors carried out with the parallel algorithm presented in Ref. [9]. The paper is organized as follows. The rest of Section 1 discusses related work and the contributions made by this paper. Section 2 describes the impact of tracking errors in heliostat fields for solar tower power plants. Section 3 discusses the heliostat control system developed in this work. Performance evaluation presented in Section 4 is made emulating a heliostat with a pan/tilt system. Section 5 contains the discussion and some conclusions are drawn in Section 6.

1.1. Related works

Several studies have been carried out addressing the need to increase the accuracy of heliostat fields and to limit costs of solar tower power plants. The current trend is to use an open-loop local controller with some minor closed-loop adjustments [7].

Open-loop control systems estimate the position of the sun according to the time of day and the geographical coordinates of the site [8]. The site location is determined using a GPS receiver while the sun's position can be evaluated through astronomical calculations [10,11]. A control algorithm uses these data together with the position of the tower to compute the correct tilt angles of each heliostat.

In order to minimize the target deviation and to achieve high precision these systems rely on robust and accurate mechanical designs. However the lack of feedback makes the control system prone to error. The most common errors, as reported in Ref. [7] are:

- errors in the sun model description;
- errors in latitude and longitude of the site;
- heliostat tracking errors;
- time-varying astigmatism of heliostats;
- accuracy of the control interval;
- structural, mechanical and installation tolerances.

To overcome some of these errors, open-loop controllers with minor adjustments were proposed. The system presented in Ref. [12] aims to correct errors related to the calculation of the sun's position and those relative to mechanical tolerance (joints, encoder) using a black and white CCD camera. The CCD camera captures images of the sun reflected by each heliostat onto a secondary target. These images are used as feedback information enabling the distance between the target center and the sunbeam centroid to be calculated, so that this error signal can be used for adjustment purposes. This approach is typically used once a week to correct heliostat positioning offset.

To surmount the deviation of the open-loop scheme [13], presents a sensor designed to determine the incident angle of irradiation using a set of photo-diodes. This system, located on the path between the heliostat and the tower, gives a feedback control signal, which duly processed, detects approximately a milliradian displacement of the mirrored sun. However, this approach increases the complexity of the plant since it requires the sensor to be precisely positioned during installation. In addition clouds could change the sensor output signal. In Ref. [14] a heliostat equipped with a photo-sensor sun-tracking system was developed and evaluated. The sensor was composed of a set of two photo-cells placed side by side on the bottom of the small box. Sun-tracking was achieved by rotating the heliostat equipped with the sensor, while maintaining the two photo-cells under illumination by the sun through a slit in the box. An angular error within 2 mrad was achieved in fine weather. However in cloudy weather the error rises up to 10 mrad.

A closed-loop sun tracking system was proposed in Ref. [15]. This controller uses four CCD cameras to image a heliostat and correct the pointing based on an analytical estimation of the expected heliostat contour. It is able to achieve sun-tracking with an error of 0.1 mrad. However it takes 2 min for each heliostat to detect and correct the imbalance.

1.2. Contributions by the present work

This paper investigates the effect of tracking errors in solar fields and proposes a closed-loop solar tracker based on low-cost distributed electronic devices. First, an accurate analysis of tracking errors arising in solar fields was carried out. The simulation environment used for this analysis is the parallel model presented in Ref. [9]. After the study carried out on the model, a closed-loop local controller is developed. The controller provides real-time detection and correction of heliostat tilt angles, with a view to increasing the concentration ratio.

The basic idea behind the system is to adopt a three-step approach. First, the heliostat tilt angles are calculated and the heliostat tracking is set using these data. Then the tracking reached is estimated using a MEMS-based six-axis digital e-compass. Finally the local controller checks if the tracking vector calculated through the model in the first phase corresponds to the tracking vector obtained when processing the sensor output; if not the controller computes the displacement and moves the heliostat until a convergence between the two values is reached. This approach limits heliostat tracking errors and allows the system to increase the concentration ratio. This is achieved at little increase to the complexity and cost of the plant, since it is obtained by using commercial low-cost sensors. The specific contributions of this paper may be summarized as follows:

- An analysis which allows one to estimate how tracking errors affect the energy concentration ratio collected on the receiver depending on the heliostat-receiver distance;
- A closed-loop sun tracker based on low-cost electronic devices, designed to make up for the lack of a feedback loop in heliostat controllers;
- A proof of concept device demonstrates the effectiveness of the proposed approach in reducing tracking errors and increasing the concentration ratio on the receiver surface. It is based on a pan tilt system emulating a heliostat.

2. Tracking error analysis

2.1. Mathematical formulation of the problem

Let us consider the subsystem sun-heliostat-absorber as shown in Fig. 1. In order to collect solar radiation, Snell's law requires that the angle of incidence θ_i be equal to the angle of reflection. The cosine of this angle can be derived from the scalar product between sun ray unit vector S and aim point unit vector R as reported in Refs. [6, Chapter 8] [9]

$$\cos(2\,\theta_i) = S \cdot R \tag{1}$$

where unit vectors S and R can be written as:

$$S = S_n\hat{i} + S_e\hat{j} + S_z\hat{k} \quad \text{and} \quad R = R_n\hat{i} + R_e\hat{j} + R_z\hat{k} \tag{2}$$

S_n, S_e, S_z and R_n, R_e, R_z, represent the direction cosines, where i, j and k are unit vectors along n, e, and z axes. The sun vector is computed using the algorithm proposed in Ref. [10]. The reflection surface unit normal H is calculated by adding the sun ray unit vector

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