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Collaborative distributed sun-tracking control system for building integration with minimal plant area and maximum energy-conversion efficiency

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ABSTRACT

This paper presents a collaborative distributed sun-tracking control system for a novel Fixed Mirror Solar Concentrator (FMSC) structure, which increases the energy-conversion efficiency of the FMSC and reduces the space between solar collectors units, a positive aspect for in-building integration. The improved FMSC uses solar concentration collectors suited for mid-range thermal applications (90–200 °C) and is designed for easy installation in buildings because of its relatively small extension. The proposed solar orientation system (ORSYS) relies on a two-step algorithm to increase the energy captured by the receiver, which provides tolerance to common logical and mechanical errors in the estimation of the receiver position. ORSYS is implemented as a CAN-based distributed system, extended with web-interface features for supervision and configuration of the overall system. ORSYS also includes a coordination algorithm that allows adjacent collectors to share the physical space between them, thus reducing the total plant area. Experimental evaluation has been performed using an industrial-scale solar collector prototype, showing its feasibility and efficiency in terms of energy conversion in real environments.

Introduction

Many alternatives have been proposed for producing energy in a sustainable way. Solar energy systems are one of the approaches intensively studied, because solar energy is clean, abundant and free. This paper deals with the so-called Fixed Mirror Solar Concentrator (FMSC); a specific type of solar linear concentrator that uses a fixed reflector and a mobile receiver, and is intended to heat water up to mid-range temperature with low concentration factors (9–15 suns). This type of technology is relevant for two of the action items for research entities that the International Energy Agency (IEA) defined in a recent roadmap [1]: (i) development of solar collectors integrated in building surfaces, and (ii) development of collectors that cover the temperature range between 100 °C and 250 °C.

FMSC uses lighter structures than typical concentrator plants in which the receiver is fixed and the collector is moved to track the sun; this property specifically provides several benefits, such as reduction in the power consumption of the sun-tracking control, reduction in the number of mechanical parts, and reduction in the maintenance efforts. An optical analysis of the FMSC (conducted by the ray-tracing procedure) was presented in [2], while the thermal analysis of the FMSC geometry was discussed in [3]; both yielded satisfactory results. A prototype called CCStaR (Concentrating Collector with Stationary Reflector V0) was implemented and tested in a realistic environment [4].

Several FMSCs can be installed together, forming a so-called FMSC structure. Such structures generate higher power output because the effective area for solar energy conversion becomes the sum of the effective areas of each individual FMSC. However, in order for these types of structures to be efficient, a number of problems must be solved. First, the sun-tracking trajectory must be able to adapt to the specific locations of the collector and the sun. Second, it is important to reduce the losses of energy conversion caused by mechanical imprecisions that lead to positioning errors of the receiver. Third, in order to maximize the effective area of the solar plant, a mechanism to avoid collisions between adjacent FMSCs must be designed. Fourth, it is necessary to develop advanced remote configuration and supervision features, because

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these structures are typically installed in places with difficult access for maintenance.

The goal of this paper is to discuss our solutions to these problems and to describe how they are all integrated in a single, distributed control system called ORientation SYStem (ORSYS). The architecture of ORSYS includes a central plant controller for the whole system, plus one control module for each individual FMSC, all of them connected through a Controller Area Network (CAN) fieldbus. The name of the individual control module is *Individual Sun Track Module* (ISTM). Fig. 1 shows the basic elements of a FMSC and their locations. The CAN field bus has been selected because of its low cost and robustness, which make it one of the most popular network technologies for embedded communications [5,6].

The functionality of ORSYS includes these features:

- Two algorithms for sun tracking: one providing *coarse* adjustment of the receiver's position, which relies on the geometric conversion of a conventional algorithm based on solar time [7]; and one providing *fine* adjustment, which uses a radiation sensor (the one shown in Fig. 1) and relies on performance estimation for reducing the imprecision caused by mechanical and orientation errors. The latter is called FAM, which stands for Fine Adjust Method.
- A mechanism for cooperation among FMSCs, intended to avoid collisions between adjacent receivers.
- A Web interface that allows configuration, management and maintenance of the internal system parameters stored in the ISTMs. In addition, the TCP/IP interface allows both local and remote access to the solar plant system management.

The rest of the paper is organized as follows. Section 'Related work' discussed related work in the area of solar plants. Section 'ORSYS architecture' introduces the ORSYS modules and the hierarchical architecture of ORSYS. The fundamentals of sun-track algorithms, and the specific details of the one implemented by ORSYS are described in Section 'ORSYS sun-tracking algorithm'. Section 'Distributed control methodology' discusses the distributed control mechanism defined for reducing the space between modules. Section 'Experimental results' discusses the experimental results and, finally, Section 'Conclusions' presents the main conclusions and gives some insight for further research.

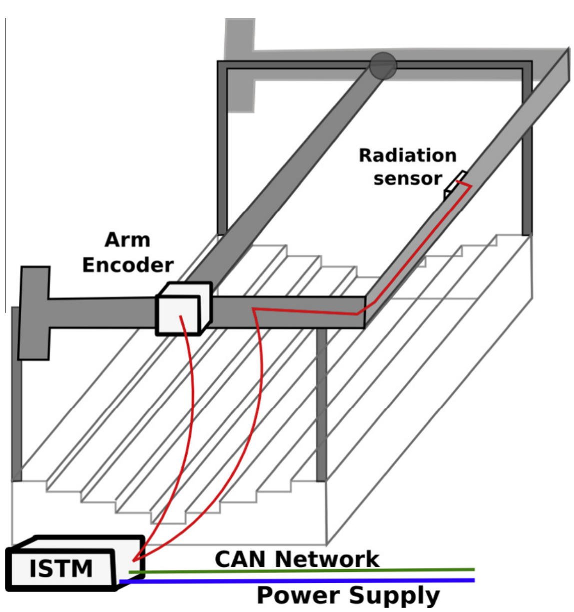

Fig. 1. Fixed Mirror Solar Concentrator structure with radiation sensors, arm encoder and Individual Sun-Tracking Module (ISTM).

Related work

A typical solar-concentrating power plant with high levels of concentration factor (more than 100 suns) has large mirrors (heliostats) with orientation capability used to reflect the sunlight onto a central receiver. These heliostats, placed around a central receiver, are formed by heavy supporting structures with large reflective surfaces and must track the sun position avoiding shadows between them and reflecting its energy onto the receiver [8].

Several *closed-loop* systems have been proposed in the literature to increase the sun-tracking algorithm accuracy by reducing the error sources that impact severely on the energy conversion efficiency. In [9] the authors propose to correct the heliostat offset error using a B/W CCD camera to correct the reflected sunrays image formed onto the receiver. This solution imitates the same procedure followed by the maintenance operators and tries to solve the error offset by monitoring the total sun projection onto the receiver, and a central controller decides the position of each heliostat that reduces the sunbeam centroid offset on the tower. In contrast, the authors of [10] introduce an individual heliostat closed-loop control system based on an incident-radiation angle sensor device capable of determining the sun position using the sunrays incident angle. In this case, the error correction is performed at the controller system of each heliostat. The work proposes a distributed solution, supposing that a well-oriented heliostat produces the required sunbeam onto the receiver.

Unfortunately, the conventional solar-concentrating plant needs a broad area extension to distribute the heliostats, and the central receiver must be usually located in an elevated position over the heliostats [8–10]. These features make those solar organization plants not practical for reduced extensions or for in-building integration.

In the case of reduced solar water heaters, the most widely used system relies on a forced-circulation system in which the collector uses the sun radiation to increase the water temperature to a typical temperature range of (50–90 °C). In the last years, the design of structures based on solar concentration collectors and suited for mid-range thermal applications, reduced extension and in-building integration has received much attention from the solar energy industry; and several interesting projects have been developed both by industry and by academy [11–13].

Tecnologia Solar Concentradora S.L. has proposed and explored the benefits of developing an efficient roof-integrated solar concentration collector suited for mid-range thermal applications, like absorption cooling and industrial heat (90–200 °C). Such systems have proven to be well suited for the development of Combined Solar Heat and Power (CHP) systems, systems which integrate photovoltaic and thermal converters in the same unit [14].

ORSYS architecture

Collector structure

The Fixed Mirror Solar Concentrator (FMSC) appeared in the seventies as a result of the oil crisis and the high prices of parabolic through collectors. The prototypes of the seventies were manufactured for the purpose of electricity generation in power plants [4]. A detailed optical analysis shows clearly that it is possible to achieve a high optical efficiency for the objective concentration range [2]. Maintaining the bigger part of the reflector static is suitable for the design of building-integrated structures as it can be used to cover facades, roofs or other architectural structures.