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Development of a fiber daylighting system based on the parallel mechanism and direct focus detection

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Abstract

In this paper, a fiber optic daylighting system based on the parallel mechanism is designed and fabricated. This system is composed of 49 concentrating cells, which are arranged in a 7×7 array. The array consists of 48 sunlight-collecting cells and a sun position sensor using direct focus detection. A linear actuator, which is composed of two stepper motors and two roller screws, is used to drive the concentrating array to track the sun with the movement in a plane parallel to the plane containing the array of fiber optic collecting aperture. The solid angle of the sun tracking angle range for the concentrating cells is $4\pi/3$ sr (covering 2/3 of the sky), satisfying the demand for 8 h of tracking. This system is suitable for building integration because it has a compact and flat shape. The sun position sensor consists of photodiodes and a fiber array in the shape of a cross. The sun position sensor can directly measure the high flux density of the focus (2500 suns). A series of tests were performed using a lux meter and spectrometer to investigate the photometric characteristics of the system for a lightless underpass of $8.6\ \text{m} \times 4.2\ \text{m} \times 2.3\ \text{m}$. The experiments show that the transfer efficiency of this system can reach 25% (with a 10-m long fiber). The luminous efficacy can reach 250 lum/W, which is two times than that of natural light because the fiber can filter out infrared light. The experiments also verified the feasibility of the daylighting system using the parallel mechanism and a direct detection device for highly concentrated light.

Keywords: Fiber; Daylighting; Tracking

1. Introduction

In many countries, illumination accounts for more than 15% of the total power consumption. Considering the low efficiency of ordinary lights and the increasing number of residents, the proportion of power consumption for illumination is continuously increasing (Olgyay and Egan, 2001). Introducing natural light into buildings for illumination will both significantly alleviate lighting and cooling loads and create a sound working environment and, thus, benefit the physical and psychological health of the inhabitants (Schlegel and et al., 2004; Tzempelikos et al., 2007). In addition to light pipes, there are two types of solar tracking daylighting systems, including heliostat and fiber optical daylighting (Kim and Kim, 2010; Wong and Yang, 2012; Feuermann and Gordon, 1999). Fiber optic daylighting transports daylight through fibers. These fibers can transfer natural light around bends. Due to the flexibility of the fiber, active lighting schemes allow for flexibility in applying sunlight for indoor illumination, using it more aggressively. In recent years, this technology has gained considerable attention and support from society (Wong and Yang, 2012; Feuermann and Gordon, 1999; Earl et al., 2003;

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Briot and Martinet, 2013; Azulay and et al., 2014). It promotes the overall affordability of using natural daylight by eliminating physical constraints in illuminating building interiors, such as the shape and orientation of a room or window or the altitude of the sun, of which passive systems may be subjected to.

At present, the type of daylight illumination system based on serial mechanism driving model is available in the market. The architectures of the fiber optic daylighting systems mentioned above all have serial mechanisms. The serial mechanism has the advantage of a simple structure, and it is easy to control. However, daylighting systems with a serial mechanism have towering shapes and are prone to high wind drag (Song et al., 2013). Additionally, their large rotation space is difficult for building integration (Han, 2010). Therefore, there is a trend to adapt building integration designs to solve the problem of wind drag. It is widely accepted that aesthetics must be taken into account in addition to function. In the building-integrated photovoltaic and building-integrated solar thermal fields, the plate profile was the most recommended structure (Han, 2010; Urbanetz et al., 2011). The advantage of a plate profile for a fiber optic daylighting system is obvious when subjected to high wind velocities. The plate profile experiences relative low wind drag, requiring a less expensive foundation to hold them when placed on roofs or hung on the walls of buildings (Pratt and Kopp, 2013; Stathopoulos et al., 2014).

A parallel manipulator is a mechanical system that uses several computer-controlled serial chains to support a single platform, or end-effector. Perhaps, the best known parallel manipulator is formed from six linear actuators that support a movable base for devices such as flight simulators. This device is called a Stewart platform or the Gough–Stewart platform in recognition of the engineers who first designed and used them (Briot and Martinet, 2013).

Their parallel distinction, as opposed to a serial manipulator, is that the end effector of this linkage is connected to its base by a number of (usually two, three or six) separate and independent linkages working in parallel. 'Parallel' is used here in the computer science sense, rather than the geometrical; these linkages act together, but it is not implied that they are aligned as parallel lines; here parallel means that the position of the end point of each linkage is independent of the position of the other linkages. A further advantage of the parallel manipulator is that the heavy actuators may often be centrally mounted on a single base platform, the movement of the arm taking place through struts and joints alone. This reduction in mass along the arm permits a lighter arm construction, thus lighter actuators and faster movements. This centralisation of mass also reduces the robot's overall moment of inertia, which may be an advantage for a mobile or walking robot (Azulay and et al., 2014).

This design inspired us to use the parallel mechanism to track the sun. Compared to the serial mechanism, the parallel mechanism has the advantage of compact size and high stiffness. The flat shape is conducive to reducing the wind resistance and good for aesthetics, making it suitable for building integration. The motion amplitude range of a daylighting system with the parallel mechanism is smaller and cannot rotate 360° like a serial mechanism. However, the system, especially a daylighting system, only needs to track the sun in the daytime. A tracking angle range of ±60° can guarantee 8 h of lighting during the workday. One purpose of this study is to design and evaluate the feasibility of using the parallel mechanism to drive a concentrator array to track sunlight for fiber optic daylighting, which is rather easy to install and gives an advantage in its appearance as the installation is not obtrusive.

For the sun tracking system based on the parallel mechanism, there is a coupling relationship between the altitude and azimuth angle of the sun. Therefore, a photosensitive sensor is needed to provide a feedback signal instead of angle encoders. A sun position sensor using direct focus detection based on optical fibers was developed in this study. In contrast to a traditional photosensitive sun position mechanism, this developed sensor can be used to detect a highly focused spot (as high as 2500 suns), and it can accurately determine the location information of a focused spot. These features make it useful as a sun-tracking device in a daylighting system.

Efficiency and illumination distribution are important parameters of a daylighting system (Wong and Yang, 2012; Feuermann and Gordon, 1999; Earl et al., 2003). In this paper, detailed tests on this system were performed to determine these parameters, and the precise spectrum of the output flux of the daylighting system was measured and successfully used to explain its excellent luminous efficacy.

2. System configurations

2.1. Parallel mechanism for solar tracking

Figs. 1 and 2 show the fiber optic daylighting system developed in this work. As shown in the two figures, the

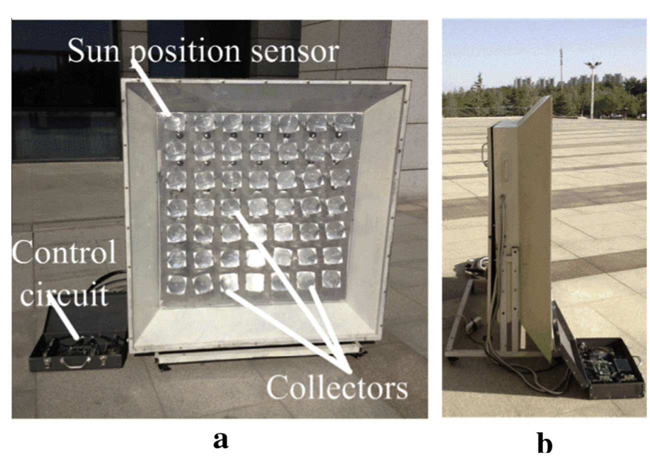

Fig. 1. Vertical setting of the prototype fiber optic daylighting system. (a) Front view and (b) side view.