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A heliostat based on a three degree-of-freedom parallel manipulator

R.B. Ashith Shyam, Mohit Acharya, A. Ghosal*

Mechanical Engineering, Indian Institute of Science, Bangalore, India

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ABSTRACT

In this paper, we propose a three-degree-of-freedom spatial parallel manipulator to track the sun in central receiver tower based concentrated solar power systems. The proposed parallel manipulator consists of three 'legs' each containing a passive rotary(R) joint, an actuated sliding or prismatic (P) joint and a passive spherical (S) joint and is known in literature as the 3-RPS manipulator. In contrast to existing serial mechanisms with two degrees-of-freedom, firstly it is shown that the extra actuator and enhanced mobility helps in reducing spillage losses and astigmatic aberration. Secondly, due to the three points of support, the beam pointing errors are less for wind and gravity loading or, alternately, the weight of the supporting structure to maintain desired deflections of the mirrors are significantly lower. Finally, the linear actuators used in the parallel manipulator do not require the use of large, accurate and expensive speed reducers. In this paper, we model the 3-RPS manipulator and derive the kinematics equations which give the motion of the linear actuators required to track the sun and reflect the incident solar energy at a stationary target at any time of the day, at any day of the year and at any location on the surface of the Earth. Finite element analysis is used to determine an optimized design which can reduce the weight of the supporting structure by as much as 60% as compared to the existing tracking mechanisms. A proportional, integral plus derivative (PID) control strategy using a low-cost processor is devised and a detailed simulation study is carried out to show that the proposed parallel manipulator performs better compared to the current tracking algorithms. Finally, a prototype of the parallel manipulator is manufactured and it is demonstrated that it is capable of performing autonomous sun tracking with the above mentioned advantages.

1. Introduction

The use of spatial parallel mechanisms have been gaining widespread acceptance in application specific purposes like camera orientation, scanning spherically shaped objects, beam aiming etc. (see, for example, (Dunlop and Jones, 1999; Li et al., 2006; Gosselin and Caron, 1999; Carricato and Parenti-Castelli, 2004; Ruggiu, 2010)). Recently, Cammarata (2015) has shown that by employing a large workspace two-degree-of-freedom (DOF) parallel manipulator for orienting photovoltaic (PV) panels, there can be an increase in electrical energy production by more than 17%. Altuzarra et al. (2014) proposed a complicated four degree-of-freedom parallel manipulator where the collector initially is kept (before the tracking starts) high above the ground and by letting it fall, under gravity, in a controlled manner using four sliders attached to it, the required orientation is achieved. This mechanism casts its own shadow on the collector and although, simulation results seem to be good, no prototype has been made and tested. Google Inc. (2017a,b) developed a novel method, using electric cable drives, for changing the position and orientation of the reflector (mirror). Although they claim that this method would reduce the power consumption for tracking, the size and cost of the actuator system, their light weight frame design is susceptible to wind gusts and could be used only at places where wind velocities are very low.

In a central receiver (CR) system, the mirrors reflect the incident sun rays onto a stationary receiver tower throughout the day. The receiver tower may be several meters (70–195 m) high and the mirrors could be as far as 1.40 km away from the tower. The motion of the moving mirrors or heliostats are programmable and also calibrated periodically to ensure that the incident rays are always reflected to the receiver tower for all instants of time during a day and throughout a year. The receiver has a heat absorbing medium, like molten salts or steam, to absorb the thermal energy and this thermal energy is converted to electricity to satisfy the load – a storage enables CR systems to produce electricity even after dark and an installation named Crescent Dunes has 10 h of dispatchable storage (Mendelsohn et al., 2012). Due to the large number of heliostats reflecting the sun's energy to the receiver,

* Corresponding author.
E-mail addresses: shyamashi@gmail.com (R.B. Ashith Shyam), mohit.m.acharya@gmail.com (M. Acharya), asitava@mecheng.iisc.ernet.in (A. Ghosal).
URL: http://www.mecheng.iisc.ernet.in/asitava/ (A. Ghosal).

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Nomenclature

γ	angle which the X axis of the $\{B\}$ makes with the East direction
$\overrightarrow{GS}$	Sun vector
ψ	Heliostat's angular location with respect to the local East direction
ρ	density of air
$\{B\}$	base co-ordinate system
$\{M\}$	mirror co-ordinate system
C_d	coefficient of drag
FoS	factor of safety
r_b	radius of the base equilateral triangle
R_d	heliostat radial distance from the tower
r_p	radius of the platform equilateral triangle
CR	Central Receiver
DOF	Degree of Freedom
OX-OY-OZ	Global co-ordinate system pointing to local East-local North and Zenith, respectively

the temperature achieved can be very high (565 °C at Ivanpah, USA (NREL, 2017)) and thus a higher efficiency is achieved in conversion to electrical energy when compared to photo-voltaic (PV) systems (Roman et al., 2006). In the existing CR systems, the mirrors are mounted as end-effector of a serial manipulator and essentially supported at the center. Due to such an arrangement, the deflection of the heliostats in presence of wind gusts may go beyond the acceptable beam error limit of 2–3 mrad (Vant-Hull, 2012). To minimize such degradation of solar image on the receiver aperture, a heavy backing or support structure needs to be provided.

The sun moves roughly in a East-West direction in a day and in a North-South direction with the seasons. Hence, two angles are involved and a two-DOF mechanism is required to track the sun. There are several serial arrangements and corresponding tracking algorithms in use (see Lipps and Vant-Hull, 1978; Mousazadeh et al., 2009; Lee et al., 2009) of which the most commonly used is the azimuth-elevation (Az-El) mount. In Az-El mount, the mirror is rotated consecutively about the azimuth and elevation angles. It was pointed out by Igel and Hughes (1979) that the astigmatic aberration of the Az-El tracking method could be reduced if the heliostats are rotated about the mirror normal in addition to the azimuth and elevation rotations thus making it a 3-DOF system. This concept later led to the development of target-aligned (T-A or spinning-elevation) heliostat where the mirror rotates about a line connecting the mirror center to the receiver (or target). The T-A method was first proposed by Ries and Schubnell (1990) and Zaibel et al. (1995) to overcome certain short comings like astigmatism, hot spots etc. of Az-El mount. Several authors (see Chen et al., 2001; Wei et al., 2011; Guo et al., 2010), independently derived the formulas for sun tracking for the T-A heliostat. Although, the T-A was developed to overcome the short comings of the Az-El method, in a comparative study of Az-El and T-A heliostats by Chen et al. (2004), it is shown that for certain times of the day and year, the Az-El performs better than T-A in terms of spillage losses and concentration.

Another exciting tracking methodology is the pitch-roll or tip-tilt using two linear actuators. Reference (Lindberg and Maki, 2010) gives a detailed account of the stress analysis in presence of gravity and wind for the pitch-roll heliostat and a complete vector-based inverse kinematic solution of the pitch-roll heliostat was provided by Freeman et al. (2017,). One of the main advantages of such a system over the Az-El is that it uses less ground space. The Stellio heliostat (Balz et al., 2016; Arbes et al., 2016) uses two linear actuators in what is called a slope-drive configuration. This type of drive eliminates the high velocity required for large change in azimuth especially when the heliostat normal reaches the vertical. Such a drive cannot be used for all heliostats in the field due to mechanical restrictions and the maximum angular distance that it can traverse is around 110°.

The two DOF parallel manipulator described in reference (Cammarata, 2015) was developed for PV systems and cannot be used for CR systems. The main reason is that for a PV system all panels in the field rotate in the same way to track the sun. However in a CR system, the heliostats are arranged around the receiver and each heliostat must rotate in a unique way to reflect the incident solar energy to the distant stationary receiver – one can intuitively see that a heliostat in the East direction need to move differently than one in the North direction and the motion will be different depending on the distance of the heliostat from the central receiver. To the best of our knowledge there are no other parallel manipulators proposed for sun tracking in CR systems in literature.

From the literatures available, it is clear that structural weight, astigmatic aberration, spillage loss and increasing energy output by improving the pointing accuracy of the end effector are some of the major concerns among researchers across the world. This work addresses some of these issues by making use of a 3-DOF spatial parallel manipulator with three 'legs' with each 'leg' containing a passive rotary (R) joint fixed at the base, a sliding or prismatic (P) joint actuated by a linear actuator and a passive spherical (S) (ball) joint connected to the moving platform. It is shown that this 3-DOF parallel manipulator – also known as the 3-RPS manipulator – can track the apparent motion of the sun autonomously in CR systems. This parallel manipulator is chosen due to its inherent advantages such as high pointing accuracy, high stiffness, availability of parameters which can be used for optimization to reduce weight and deflection of the mirror due to wind gusts and self loading, possibility of using low cost linear actuators and avoiding large and accurate gear reduction to track the slow moving sun and ease of solving inverse kinematics for real time control. This work deals with the analysis, design, prototyping and experimental validation of a 3-RPS parallel manipulator for sun tracking in CR systems.

This paper is organized as follows: In Section 2, the geometry of the 3-RPS manipulator and the preliminaries required to understand sun tracking in CR systems are presented. It also presents the kinematic equations which form the basis of algorithm development. A detailed description of an iterative search method to obtain least structural weight and find the various design parameters which govern the actuations required and spillage loss are given in Section 3. Section 4 gives the results obtained during the simulation study conducted. Section 5 presents a detailed description of prototyping and experiments done with the 3-RPS parallel manipulator and Section 6 presents the conclusions of this work.

2. The 3-RPS parallel manipulator

Fig. 1 shows the schematic diagram of a 3-RPS heliostat reflecting the incident solar radiations to the receiver tower. The relative motion of the sun in the sky with respect to earth is known completely from the knowledge of date, time and location on the Earth's surface and hence the sun vector, $\overrightarrow{GS}$, is known. Referring to Fig. 1, let O represents the origin of a global or fixed co-ordinate system located at the base of the receiver tower and the OX, OY and OZ axes pointing towards the East, North and Zenith directions, respectively. The location of the heliostat on the surround solar field described by point O_1 is specified by the distance, R_d, from O and the angle ψ with respect to the OX axis. The base co-ordinate system at the heliostat, $\{B\}$, has its origin at O_1 and axes x_b, y_b and z_b are described with respect to the fixed coordinate system by a rotation γ about the Z axis. The platform or mirror coordinate system, $\{M\}$, is located at G with axes x_m, y_m and z_m as shown. The reference point on the platform, G, is given by the vector $\overrightarrow{O_1G}$ having co-