Mechanism and Machine Theory 119 (2018) 130–141

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmachtheory

Research paper

Path planning of a 3-UPU wrist manipulator for sun tracking in central receiver tower systems

R.B. Ashith Shyam[a], A. Ghosal[b,*]

[a] Research Scholar, Mechanical Engineering, Indian Institute of Science, Bangalore, India
[b] Mechanical Engineering, Indian Institute of Science, Bangalore, India

ARTICLE INFO

Article history:
Received 19 June 2017
Revised 7 August 2017
Accepted 25 August 2017

Keywords:
Heliostat
3-UPU wrist
Sun tracking
Parallel manipulator
Central receiver
PID control

ABSTRACT

Heliostats capable of tracking the sun as it moves across the sky and focusing the incident solar energy on to a central receiver tower requires a two degree-of-freedom (DOF) mechanism which can orient the mirror in the desired manner. Existing two-DOF mechanism, such as the Azimuth-Elevation (Az-EL) and the Target-Aligned (T-A), have two actuators in series. It is known that during certain times of the day, the T-A configuration has less spillage losses and astigmatic aberration while at other times the Az-El configuration is better. In this paper, we propose a three-DOF parallel manipulator which can be used as a heliostat. The proposed 3-UPU, three-DOF parallel manipulator, has a fixed point about which the mirror can rotate about three axes. Since only two DOF are required to track the sun, the 3-UPU is a redundant system. We propose a strategy to use this redundancy and electronically reconfigure the 3-UPU to achieve the Az-El and T-A configurations thus achieving the advantages of both. As the motion of the sun is precisely known for any geographical location on earth, time and day of the year, numerical simulations done a priori provide the conditions for switching.

1. Introduction

From the time parallel manipulators were first introduced by Gough [1] and Stewart [2], it has been known that they provide high structural rigidity and more accurate positioning and orientation of the end-effector or the moving platform [3]. The increased rigidity is due to the fact that the moving platform is supported at multiple points thereby the external load is shared. The increased accuracy is due to the fact that the positioning and pointing error of the end-effector is a function of the largest error in any actuator and *not* the sum of the errors as in a serial arrangement. Due to these inherent advantages, parallel manipulators have been extensively used in flight simulators, precision manufacturing, pointing devices, medical applications, and, more recently, in video games. In harvesting solar energy, one approach is to reflect the incident solar radiation by mirrors on to a stationary central receiver (CR). At the central receiver, the reflected solar thermal radiation from several such mirrors are converted to electricity. As the Earth rotates during the day and around the sun, the sun traces a well-defined path in the sky and to continuously reflect the solar radiation, the mirror has to rotate about two axis. The device including the mirror and the actuators required to rotate the mirror assembly is called

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

http://dx.doi.org/10.1016/j.mechmachtheory.2017.08.019
0094-114X/

a heliostat and traditionally the two rotation axis of a heliostat and the two actuators are in series. In the well-known Azimuth-Elevation (Az-El) arrangement, as the name implies, the mirror is rotated about the azimuth and the elevation axes. In another configuration, the mirror is rotated about a line connecting the mirror centre to the stationary receiver centre and about the elevation – this is known as the Target-Aligned (T-A) or the Spinning-Elevation arrangement. The pointing accuracy requirement for a typical heliostat is 2–3 mrad and the heliostat is expected to track the sun in the presence of wind and gravity loading (see reference [4] for more details on heliostat and sun tracking). Meeting these requirements, in a CR system with thousands of heliostats, results in the cost of the heliostats of about 40–50% of the total installation cost [5]. Hence, attempts are being made worldwide to reduce the cost of the heliostat so as to make a CR system competitive with other ways (like photo–voltaics) to harvest incident solar energy. Due to the inherent advantages of increased structural rigidity, a platform type parallel manipulator can carry larger mirror or require less structural supporting material to maintain the required low deformation. Due to the inherent increased positioning and orientation accuracy in a platform type parallel manipulator, it is expected that the required pointing accuracy can be more easily satisfied or less accurate actuators can be used to achieve the required pointing accuracy. Both these aspects can lead to reduction in cost of a heliostat and this is the main motivation behind using a platform type manipulator over the traditional serial Az-El and T-A configuration heliostats. In this paper, we propose the use of a three-degree-of-freedom parallel manipulator for sun tracking in concentrated solar power systems.

There have been a few attempts to use parallel manipulators in sun tracking. In the work by [6], a two degree-of-freedom parallel manipulator called the U-2PUS has been developed for photo-voltaic (PV) systems. The author claims that this manipulator is ideal for photo-voltaic systems in latitudes from 0 to 50°. This parallel manipulator could be used for photo-voltaic systems but cannot be used for central receiver (CR) systems since in a field with photo-voltaic panels, all the PV panels are tracked in a similar manner. There is no reflection of the incident solar radiation and the conversion to electricity takes place in the PV panel itself. The location of the PV panels in the field do not play any part as the sun's rays are parallel everywhere. For central receiver systems, the heliostats at different locations in the field will have different motion if the incident energy is to be reflected to a central receiver. Mathematically, it can be shown that there are more unknowns than equations available in the U-2PUS parallel manipulator system and hence it cannot be used in a CR system. A four degree-of-freedom parallel manipulator is proposed for sun-tracking in [7]. In this work, the collector which is initially kept high above the ground is allowed to fall down in a controlled manner under the influence of gravity thereby attaining the required orientation. One major drawback of this manipulator is that it casts its own shadow on the collector and no prototype has been made to check the veracity of the claims. Google's Heliostat Optical Simulation tool (HOpS) [8] is an attempt to do sun tracking in CR systems by the use of cable attached mirrors. Although there are some advantages to the system, this can be used only in places where the wind speeds are very low. Several other two degree-of-freedom (DOF) spherical mechanisms (see references [9–12]) for application specific purposes such as camera orientation, scanning spherically shaped items etc. are described in literature but none of these have been shown to be capable of tracking the sun for central receiver systems.

A new type of tracking strategy which is independent of latitude has been proposed in [13]. The authors claim to have introduced some advantages in mechatronic control schemes, high optical efficiency by operating the heliostat at a very narrow range of incident angles. Another interesting strategy called an integer linear programming is developed for optimizing the aiming strategy [14] and thus to control the spike on the receiver aperture temperature thereby preventing its damage. The pitch-roll and slopedrive tracking (see references [15–18]) mechanisms are gaining popularity and has been employed in the CSIRO and Stellio heliostats.

In this work, the focus is on CR systems and we propose a parallel manipulator, viz., the 3-UPU wrist that can be used for sun tracking in CR systems without any of the above mentioned disadvantages. The 'U' denotes a two-DOF Hooke joint, the 'P' denotes single DOF a prismatic or sliding joint. In the parallel manipulator, the 'P' joint is actuated and the other joints are not actuated or are passive. In addition, the 3-UPU can be reconfigured to be used either in Azimuth-Elevation (Az-El) or in the Target-Aligned (T-A or spinning-elevation) method thus combining the advantages of both by simply changing software and control strategy and *does not* require any change in the hardware. The 3-UPU wrist can thus be operated in a mode which gives the best performance in terms of spillage losses or astigmatism at a particular time of the day or a date in the year. In the parallel configuration, linear actuators are used. The motion of the prismatic (P) joints or the stroke of the linear actuators are computed using inverse kinematics algorithms and adjusted with respect to time to achieve the orientation required for sun tracking. The parallel manipulator requires three actuators as opposed to two in the Az-El and T-A configurations. However, since the support material is less [19] or larger mirrors can be used and less expensive and less accurate linear actuators can be used, the overall cost of the plant is expected to be less.

The paper is organized as follows: Section 2 gives the kinematics of the 3-UPU wrist and the rotation matrix for both the Az-EL and T-A heliostat are obtained. From a desired rotation matrix, the actuations at the P joints are computed. In Section 3, simulations carried out for Bangalore and Rajasthan, India on the feasibility of using a 3-UPU wrist as a sun tracker in CR systems is presented. Section 4 shows the prototype design, the controller used, the results from actual sun tracking experiments performed and the observations made during the experiment. Finally, Section 5 summarizes the work done and gives an insight into the future directions of research.