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Kinematics analysis and workspace investigation of a novel 2-DOF parallel manipulator applied in vehicle driving simulator

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ABSTRACT

A novel two degree of freedom (DOF) parallel manipulator with 3 legs, which is applied in vehicle driving simulator, is proposed in this paper. Kinematics and workspace of the proposed parallel manipulator are systematically studied. The proposed mechanism with two rotations includes the bottom fixed platform, two servo electrical cylinders, one supporting pillar, the top platform and some joints. First the kinematics characteristics of the 2-DOF parallel manipulator are analyzed and geometric description are given. Second some analytic formulae are derived for solving inverse displacement and forward displacement for the two rotations of the proposed 2-DOF mechanism. Third workspace for this 2-DOF mechanism is constructed and analyzed. The analytic results are verified by its simulation mechanism to be consistent with the calculated ones. The proposed mechanism has very simple structure and low cost and can realize two rotations in space. An example is given using in proprioceptive mechanism of vehicle driving simulator.

1. Introduction

A parallel manipulator is a closed-loop mechanism in which a moving platform is connected to a fixed base by at least two serial kinematics chains or legs. Compared with serial manipulators, parallel manipulators have some advantages in dynamic behavior, stiffness, load carrying capacity, accuracy, acceleration, compactness, and manufacturing cost. In the past two decades, parallel mechanisms have received great attention in the fields of pilot training simulators, vehicle driving simulator, high-speed machine tool, high speed pick-and-place applications, micro-motion manipulators and force/torque sensors, and so on. Generally, some performance indices, such as control accuracy (isotropy or dexterity), speed, payload capability, and stiffness will be involved in design process of parallel mechanism. Pritschow and Wurst [1] summarized the form of six degrees of freedom parallel mechanism owing to the difference of motion joint, the configuration of controller, the basic platform, and the layout of mobile platform, and proposed a design method for constructing this parallel mechanism by using table structure. Dash et al. [2] established an optimal modular design method for the six degrees of freedom parallel manipulator and a general structure design method by using the query table. Yang et al. [3] proposed a novel six freedom degree parallel mechanism by using the three same leg to support the motion platform. The axis line of all motion joint is parallel with each other besides the three spherical joint. Jin et al. [4] studied a class of branch chain with 3 symmetrical mechanisms with partial decoupling six degrees of freedom parallel manipulator design, and introduced the concept of group decoupling to the parallel manipulator motion synthesis and classification. Shen et al. [5] proposed a hybrid single-opened chain based on a stylized method, which is characterized by the mixture of single-opened chain (including the single open-chain) as parallel mechanism to achieve design output component 3 translation and 3 rotation of the seven new practical hybrid single open chain. Lu et al. [6] proposed a novel 2SPS+PRRPR parallel manipulator with 3-leg 5-DOF and studied its kinematics, statics and workspace systematically.

The workspace of a manipulator is defined as the set of all end-effectors configurations which can be reached by some choice of joints. Several kinds of workspaces can be defined, namely orientation workspace and positional workspace. With different orientation requirements, the positional workspace can be further classified into: constant orientation workspace, reachable workspace, inclusive workspace, total orientation workspace, and dexterous workspace [7]. In order to determine workspace of a parallel manipulator, various geometric or numerical methods have been proposed. Gosellin and Guillot [8] put forward a geometrical method and the proposed method was originally employed as a technique for determining the positional workspace of a 6-DOF parallel manipulator, in which its shape depends on the accelerations of the end-effectors. The numerical methods of workspace and its boundary determination were presented

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as mapping using continuation algorithms in [9] and [10]. Ceccarelli [9] proposed an algebraic formulation to describe the workspace boundary of general N–R revolute open chain manipulators. Haug et al. [10] reported the first complete treatment of the determination of cures on the boundary of manipulator workspace.

Although less-DOF spatial parallel manipulators present several advantages in terms of the device total cost reduction in manufacturing and operating, some issues become complicated in many cases such as position and orientation of the moving platform. In the less-DOF parallel mechanisms, the 2-DOF parallel mechanisms have opened new horizons for the industrial robotics designer. Enhancements in terms of speed, stability, precision and cost reduction are attainable when compared to higher degree of freedom serial designs. This comes at the cost of a reduced workspace and a more challenging dynamic analysis. The five-bar mechanism is a typical parallel mechanism with two degrees of freedom, which can be used for positioning a point on a region of a plane that is known as the workspace [11–13]. In such mechanisms, only prismatic (P) and revolute (R) joints are used. The 5R parallel mechanism, which is the most studied 2-DOF parallel mechanism, consists of five bars that are connected end to end by five revolute joints, two of which are connected to the base and are actuated. Cervantes-Sanchez and Rendon-Sanchez [14] presented a method for generating the reachable workspace of a class of planar two-degree-of-freedom end-effector-type manipulators, which was based on six planar linkages with five links and five joints. Shao et al. [15] conducted the dynamic manipulability and dynamic optimization of a two degree-of-freedom parallel manipulator. Arsenault and Gosselin [16] studied the kinematics, static and dynamics of a planar two-degree-of-freedom temerity mechanism. Solutions to the direct and inverse static problems are first presented. Liu et al. [17] addressed performance analysis and optimum design of a PRRRP 2-DOF parallel mechanism that is actuated vertically by linear actuators. Zhu and Dou [18] investigated the global conditioning index, global velocity index and global stiffness index of the 2-DOF parallel manipulators based on the kinematics model and Jacobian matrix. Carricato and Parenti-Castelli [19] presented a novel pointing parallel mechanism with fully decoupled degrees of freedom. The mechanism consists of two interconnected slider–crank linkages, each one of which independently actuates one of the Euler angles of the output link. Joshi and Tsai [20] proposed a methodology for the Jacobian analysis of limited degrees-of-freedom (DOF) parallel manipulators. The limited-DOF parallel manipulator is a spatial parallel manipulator which has less than six degrees-of-freedom. Rao and Rao [21] made dimensional synthesis of 3 degrees of freedom (DOF) spatial 3-revolute-prismatic-spherical (RPS) parallel manipulator.

In this paper, a novel 2-DOF parallel manipulator with 3 legs of having two rotations is proposed and its kinematics and workspace are studied systematically. The proposed parallel manipulator is a 2-DOF mechanism and includes the bottom fixed platform, two servo electrical cylinders, one supporting pillar, the top platform and some joints and can realize two rotations. The prototype of the 2-DOF parallel manipulator has been used to simulate proprioceptive sense of vehicle driving simulator. In addition, the parallel mechanism has some potential applications for game machine, tunnel borer and simulator teaching apparatus.

The paper is organized as follows. First geometric description of the designed 2-DOF PKM (parallel kinematics mechanism) is given in Section 2. Then kinematics analysis equation of the PKM is established and inverse kinematics and forward kinematics are discussed in Section 3. Section 4 is about workspace analysis of the proposed 2-DOF PKM and workspace of roll attitude and pitch attitude are investigated in Section 4. Section 5 is mechanism application and example verification in vehicle driving simulator. Finally conclusions are given in Section 6.

2. Geometric description of the designed 2-DOF PKM

In three dimension space, a rigid object needs the support of three points, which are not in a line, to guarantee the completeness of constraints. Based on this principle, a 2-DOF parallel mechanism is designed. The proposed 2-DOF parallel manipulator illustrated in Fig. 1 is composed of a top moving platform m, a fixed base platform B, two (spherical joint-prismatic joint-revolute joint) SPR active legs $r_i(i=2,3)$with a linear actuator for each leg, and one (spherical joint–revolute joint) supporting pillar with no actuator. Where, B is an isosceles link $\Delta A_1A_2A_3$ with three sides $l_i(i=1,2,3)$, three vertices $A_i(i=1,2,3)$. m is a plane on which there is an isosceles link $\Delta B_1B_2B_3$ with three sides $L_i(i=1,2,3)$, three vertices $B_i(i=1,2,3)$. The axis line of revolute joint at point A_2 is parallel to the side A_1A_3, and the axis line of revolute joint at point A_3 is parallel to the side A_1A_2 and the axis line of revolute joint at point A_1 is parallel to the side A_2A_3 (y axis). The points A_1, A_2, A_3 and B_1, B_2, B_3 shown in Fig. 1 define the geometry of the fixed base platform B and the top moving platform m, respectively.

In Fig. 1 we take $h=$c, $l_2=l_3=L_2=L_3=$a and $l_1=L_1=$b. The stationary coordinate system o–xyz is set up with its origin located at the center o of triangle $\Delta A_1A_2A_3$ shown in Fig. 1. Point o is also center of circumscribed circle of $\Delta A_1A_2A_3$. Axis x directs at the midpoint of connecting line of the two revolute joints which connect the kinematics chain L_{11} and the kinematics chain L_{22} with the fixed base platform. Axis z lies in the normal vector of the fixed base platform. Axis y can be established according to the right-hand ruler. The moving coordinate system O-XYZ is set up with its origins located at the center of triangle $\Delta B_1B_2B_3$ shown in Fig. 1. Point O is also center of circumscribed circle of $\Delta B_1B_2B_3$. Axis X directs at the midpoint of connecting line of the two spherical joints which connect the kinematics chain L_{11} and the kinematics chain L_{22} with the top moving platform. Axis Z lies in the normal vector of the top moving platform. Axis Y can be established according to the right-hand ruler.

In this PKM, the number of links is $g_0=7$ including a top moving platform, a fixed base platform, two SPR active leg $r_i(i=2,3)$ with a linear actuator for each leg, and one (spherical joint–revolute joint) supporting pillar with no actuator. The number of joints is $g_1=8$ including three spherical joints, three revolute joints, and two prismatic joints; the DOF of the joints is

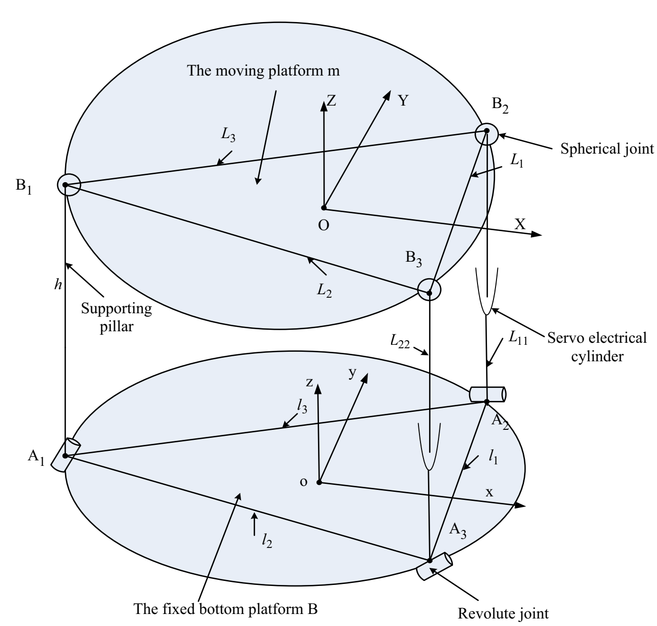

Fig. 1. Schematic diagram of 2-SPR 2-DOF PKM.