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Structural synthesis for a lower-mobility parallel kinematic machine with swivel hinges

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ABSTRACT

In this paper, a novel parallel kinematic machine is proposed. Its active platform (main supporting spindle) is manufactured with swivel hinges, that is, we substitute the spherical hinge with a swivel hinge. The active platform is also divided into several layers, which alters the characteristics of a single-layer-platform parallel machine. This paper applies a comprehensive structural approach based on position and orientation characteristics (POC). Each single open chain (SOC) is studied independently from the whole mechanism; we also analyse the POC of each kinematic pair. By the method of union, we obtain the POC matrix of the output motion of each link. Based on the verification of the 5-DOF (degree of freedom) parallel kinematic machine, we construct 3-DOF and 4-DOF parallel mechanisms with swivel hinges through the combination and union of different chains, and develop them into a series.

1. Introduction

Since the start of its application in the field of digital machines in 1994, the parallel machine has developed and become one of the most promising and intelligent types of machine. It applies multi-parallel struts instead of a fixed oriented tool, thus improving the unmatched speed between high-speed processing and the low orienting speed of the tool, which limits high-speed cutting. However, parallel machines still have several disadvantages. The complicated singularity configuration greatly hinders the continuous processing of the tool. The spherical hinge connecting the moving struts and the active platform leads to a low-rigidity point contact, and its own moving range also limits the whole motion space of the parallel machine. So, the development of a better structure for the parallel machine is of vital importance. In 2001, Dr. Michael Schwaar proposed a 5-DOF parallel machine with swivel hinges [1–3]. The novelty of this kind of machine was to replace the conventional spherical or hook joints fixed on the active platform with swivels. Five swivels, which could rotate 360°, enable the spindle to rotate 90° around axis A in the working space. The 4-DOF parallel machine [4], constructed by Thurneysen, realized a 120° rotation around axis B for the spindle. In addition, the load of the machine in the whole working space is even. Jun Wu constructed a symmetrical 3-DOF parallel manipulator with one and two additional branches [5–7] as well as a planar 2-DOF parallel manipulator with actuation redundancy [8–9], and investigated their stiffness and natural frequency. The approach of structural synthesis is basic in designing and developing new parallel machines. In the main, three methods are available [10]. The first is the screw theory. Hunt [11] invented a parallel mechanism according to this theory and met the requirement. Another is the displacement subgroup method. Park et al. [12] proposed a series of parallel robots based on this theory. The other is the position and orientation characteristics (POC) approach. Yang et al. [13] proposed a structural synthesis approach based on a single open chain (SOC). This method describes the relationship among the topological structure, POC and DOF (degree of freedom) with explicit function, and more than 200 parallel machines are generated through synthesis. All of the three methods could cover some kind of configuration, but those actually generated by these methods are not commonly seen. Until now, over 40 examples have been successfully generated around the world. Generally speaking, a basic pattern of configuration has to be designed ex ante, and the new structure could only be developed based on this mature pattern by way of derivation.

The active platform (main supporting spindle) in this paper is a parallel machine with swivel hinges. It is developed based on the one proposed by Michael Schwaar. The novelty of this machine is to replace the spherical hinges with swivels. The swivel hinges are similar to spherical hinges since they both have three DOF, as is shown in Fig. 1. Yet they are different in that the axes of the three

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rotation pairs, especially the one which is not in the same plane as the other two pairs, do not intersect at a single point. Applying swivel hinges of this kind to the parallel machine, we could limit the rotation of the active platform by fixing it with one of the swivels, mostly the nethermost. In addition, some disadvantages of the structure can be overcome and better motion characteristics could be generated. The active platform is divided into multi-layers, thus altering the characteristics of a single-layer platform and increasing the bearing points of the spindle. Better rigidity is thus obtained by such a multi-layer, single-centre platform with swivel hinges. The loading ability and stability of the spindle are also increased. Co-linearity of the configuration disappears. The swivel, which could rotate arbitrarily, enlarges the swinging range of a spindle to 90° for at least one direction. Thus the machine is capable of five-aspect processing. This paper adopts the structural synthesis approach based on POC, and constructs 3-DOF and 4-DOF parallel machines with swivel hinges based on the analysis of the 4-DOF. The general inverse kinematics solution is also obtained in this paper.

The rest of this paper is organised as follows: Section 2 describes the basic approach based on the POC and analyses the existing 5-DOF parallel machine. Each SOC is studied independently from the whole mechanism and we also analyse the POC of each kinematic pair. By the method of union, we obtain the POC matrix of the output motion of each chain. Section 3 processes the verification by comparing the existing 5-DOF parallel machine and the outcome of the union of five chains. By the structural synthesis method based on the POC, Sections 4 and 5 construct 3-DOF and 4-DOF parallel machines, analyse their properties of freedom, and develop them into a series. Section 6 deduces the general inverse kinematics solution for this series of machines with swivel hinges. Section 7 simulates the mechanical kinematics with Adams', and verifies the spatial locus of the tool tip of 5-, 4- and 3-DOF machines with the obtained inverse general solution. Section 8 is the conclusion.

2. Related work

Since we apply Cartesian coordinates, lower-mobility parallel mechanisms with 3-, 4- or 5-DOF are more suitable for machine tools. According to SOC synthesis, this paper proposes a series of lower-mobility parallel mechanisms with swivel hinges and analyses as well as verifies their properties of freedom. Our work includes two aspects: the synthesis of new structures and kinematic analysis. Unlike serial structures, reducing DOF will lead to more uncertainty in kinematics. Thus, the kinematic properties of the structure mentioned in this paper are harder to determine than those of 6-DOF machines. The method here is based on Yang's POC. The main idea is that we view the series of kinematic pairs as an SOC. The property of freedom is obtained through the method of union and then we take the intersection among all the chains, thus obtaining the property of freedom for the whole parallel mechanism. The positive calculation of the POC equation could, for example, be applied to structural analysis, given the topological structure, and to show the POC matrix for the machine end, or the instantaneous POC matrix of the singularity position. On the other hand, the inverse calculation of the POC equation could be applied to structural synthesis, for example, given the POC matrix, and to study the whole type of structure for the machine. The structure of each strut in the parallel mechanism with swivel hinges is similar, and is a serial of the kinematic pair. According to the procedure in the POC equation calculation, we analyse each chain of the 5-DOF structure shown in Fig. 1.

As is shown in Fig. 2, the rotation pairs, R_1 and R_2, are perpendicular with each other, and become a hook joint. P_3 is a motion pair moving along the strut, and the strut always keeps perpendicular with axis R_2. P_3 is a driving pair. R_4, R_5 and R_6 compose a swivel hinge. R_4 rotates around the axis of the strut. The rotation axis of R_5 is perpendicular with the strut. R_6 is the swivel connected with the active platform. Its axis line is not in the same plane with that of R_4 and R_5.

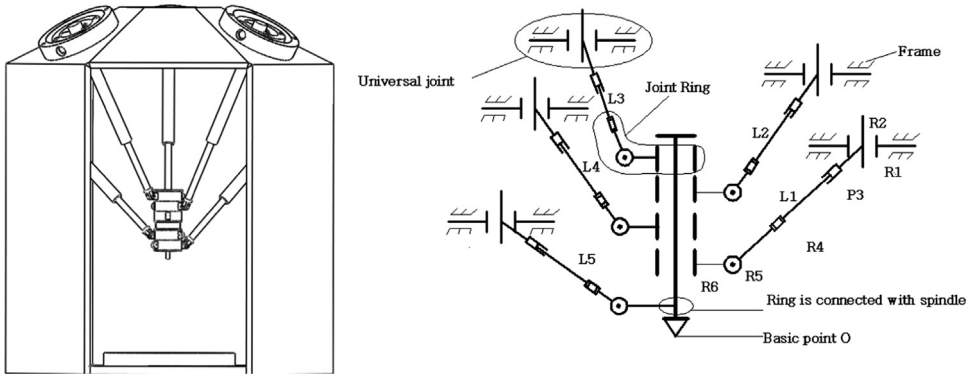

Fig. 1. The structure and mechanical arrangement of a 5-DOF parallel machine with swivel hinges.

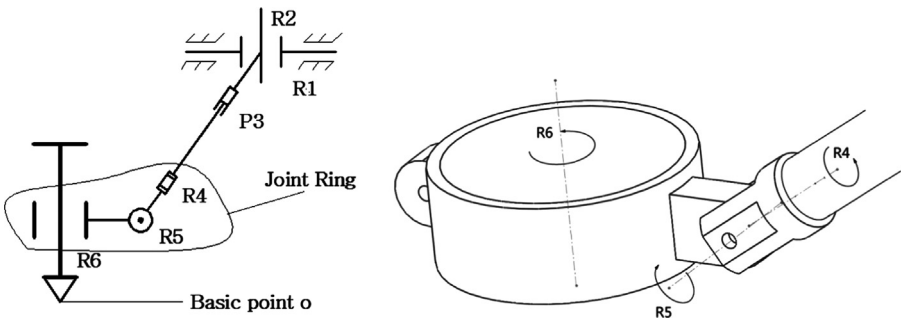

Fig. 2. Single open chain.