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Sensitivity analysis of the 3-PRS parallel kinematic spindle platform of a serial-parallel machine tool

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Abstract

The special configuration of a serial-parallel type machine tool possesses five degrees of freedom and provides more flexibility in NC machining. The parallel spindle platform plays the key role in manipulating three directions of movement. In this study, the inverse kinematics analysis of the platform is derived first. A sensitivity model of the spindle platform subject to the structure parameters is then proposed and analyzed. All the parameters influencing the position and orientation of the spindle platform are discussed based on the sensitivity model and the simulated examples. Critical parameters to the accuracy of the cutter location can then be found, which are the slider position, the strut length, and the tool length.

Keywords: Kinematic analysis; Sensitivity analysis; 3-PRS spindle platform; Serial-parallel machine tool

1. Introduction

To obtain higher accuracy and greater dexterity, machine tool manufacturers are developing parallel type structures for the next generation of machine tools. It is always a goal to pursue an interesting development in the machine tool industry that holds great promise for improving accuracy. Machine tools with their high rigidity and accuracy are ideally suited for precision applications. Parallel manipulator offers a radically different type of machine structure relative to the traditional serial type machines. It is believed that the inherent mechanical structure of the parallel type machines provides high dexterity, stiffness, accuracy and speed compared to the conventional multi-axis structure [1,2].

In the past, many comprehensive studies and works have been made in the area of parallel manipulators. The kinematic behavior of the parallel mechanism with extensible strut has been discussed in many literatures [3–5]. Some reports dealt with the kinematics of three-legged parallel manipulators [6,7]. Most of these articles focused on the discussion of both the analytical and the numerical methods to solve the kinematics of pure-parallel mechanisms [6–8]. Some papers also discussed the accuracy analysis of the Stewart platform manipulators [9–11]. A new type of serial-parallel machine tool has been developed by the Mechanical Laboratory of ITRI in Taiwan. Simulation analysis and experimental tests have shown the necessity of its accuracy enhancement [12–14].

Even though many researches have made contributions to the theory and design of the parallel kinematic mechanism, however, commercial applications of this potential parallel machine have not been widespread yet. The main obstacle to the applications of this kind of machine tool is their unsatisfactory accuracy. Similar to the traditional machine tool, there are several major factors, such as the structural imperfection, the elastic deformation and the thermal deformation, that will degrade the machine accuracy. In order to find out the essential error sources, sensitivity analysis of the spindle platform movement and error identification are neces-

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sary for the purpose of accuracy enhancement of the machine tool.

In this paper, the kinematics model of parallel mechanism is derived in the first part. Sensitivity model of the spindle platform subject to structural and kinematic parameters is then proposed. All parameters influencing the position and orientation of the spindle platform are analytically estimated. Simulated example are given to identify the most critical error sources.

2. Machine tool configuration

The machine tool under investigation is called a serial-parallel type machine tool. The configuration is shown in Fig. 1. It consists of a three-degree-of-freedom spindle platform and a conventional two-degree-of-freedom *X*–*Y* table to form a five-axis structure. The spindle is assembled in the platform, which is connected to three struts of constant length by means of ball joints (or U-joint) that are equally spaced at a nominal angle of 120°. The other end of each strut is connected to a slider with a rotational joint. Each slider can move up and down along the corresponding vertical slideway fixed to a column that is also spaced at nominal 120° angle from one another. The platform, such constructed, has one linear motion in the *Z*-axis and two angular rotations (α and β) in the *X*- and *Y*-axes, respectively. The *X*–*Y* table that supports the workpiece provides the linear motions of the workpiece in two horizontal directions. The features of this configuration are easy to manufacture and control, more accurate and larger workspace, compared to the Stewart platform-based parallel machine tool.

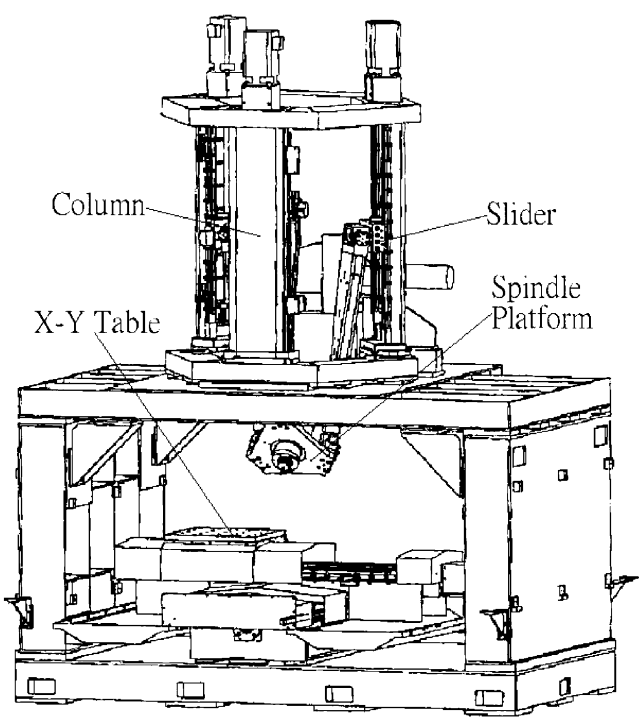

Fig. 1. Structure of the serial-parallel type machine tool.

3. Inverse kinematic analysis

In order to analyze the kinematics of the parallel mechanism, three relative coordinate frames are assigned, as shown in Fig. 2. A static Cartesian coordinate frame *XYZ* is fixed at the base of the machine tool with the *Z*-axis pointing to the vertical direction, the *X*-axis pointing toward $B_{1,}$ and the *Y*-axis pointing along the B_2B_3 line. The movable Cartesian coordinate frame, $X'Y'Z'$, is fixed at the center of the *X*–*Y* table with the same axes directions as the *XYZ* coordinate frame. The third coordinate frame, *xyz*, is assigned to the tool tip, with the *z*-axis coinciding with the spindle axis. The ball joint b_1 is located in the plane xo_Tz.

Let R and r be the radii of circles passing through joints R_i and b_i (i = 1–3), respectively. The positions of R_i referenced to the coordinate frame *XYZ* can be expressed by

$$\mathbf{R}_1 = \begin{bmatrix} \frac{3}{2}R & 0 & H_1 \end{bmatrix}^T \mathbf{R}_2 = \begin{bmatrix} 0 & \frac{\sqrt{3}}{2}R & H_2 \end{bmatrix}^T \tag{1}$$

$$\mathbf{R}_3 = \begin{bmatrix} 0 & -\frac{\sqrt{3}}{2}R & H_3 \end{bmatrix}^T$$

where H_i is the height of R_i along the *Z*-axis.

The positions of the ball joints b_i with respect to the coordinate frame *xyz* are

$$\mathbf{b}_1 = [r \;\; 0 \;\; h]^T \mathbf{b}_2 = \begin{bmatrix} -\frac{1}{2}r & \frac{\sqrt{3}}{2}r & h \end{bmatrix}^T \tag{2}$$

$$\mathbf{b}_3 = \begin{bmatrix} -\frac{1}{2}r & -\frac{\sqrt{3}}{2}r & h \end{bmatrix}^T$$

where h is the distance from the tool tip o_T to the center of the platform.

The coordinate frame *xyz* with respect to the coordinate frame *XYZ*, can be described by the homogeneous transformation matrix [**T**].