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Inverse kinematics for a novel hybrid parallel–serial five-axis machine tool

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ABSTRACT

Instead of obsessively emphasizing to interpolate more points from the linearization algorithm, the NC codes are recalculated to form a new path for the pivot that can avoid the discretization near the singularity points in this study. In previous studies, orientable-spindle machines were directly used to generate smooth tool paths traversing singular positions through inverse kinematics. In many characteristics and practices, PKMs (parallel kinematic machines) and serial machines are the opposites of each other. Fully PKMs have relatively very limited working-space, especially in terms of orientation characteristics. Fully serial machines have a problem of error accumulation. This paper presents a modular method to construct a postprocessor system for a novel hybrid parallel-serial five-axis machine tool. A hybrid parallel-serial mathematical model is introduced to analyze a structural configuration. The configuration decomposition of machine tools is used to create the kernel of the postprocessor. The proposed modified Denavit–Hartenberg notation is used in the coordinate conversion procedure, and then an algorithm is used for developing the inverse kinematics of five-axis machines. The feasibility of solutions depends on the surface normal along the tool path satisfying certain orientation constraints. The proposed algorithm can be easily adapted to convert between cutter contact path and cutter location code and implemented on computer-aided design and computer-aided manufacturing systems. Examples with end-milling and side-milling tools are demonstrated and real cutting parts are implemented for verifying the algorithm.

1. Introduction

At present, because of the increasing demand for higher-precision components, the main challenge of machining industries is to manufacture high-quality products and achieve minimal wear of cutting tools while reducing cost and time constraints. To meet this challenge of improving machining performance and conditions and minimizing production expenses, a suitable and systematic technique must be developed for machines, which ensures superior surface finish, productivity improvement, and efficient and economical machining processes. Recently, precision machining leading to a high quality and complexity level has become a trend. Machined pieces must meet the requirement of a machine tool that completes all or part of the workpieces through a minimal number of clamping operations. Therefore, a multiaxial structure is commonly used for precision machining. Machining has evolved from automated machine tools to modern multi-axis computer numerical control (CNC) machining centers, which provide more flexible and versatile control than before. The complicate frames of machine tools sometimes lead to manufacturing inaccuracies at the tool tip because of kinematic parameter deviations engendered by manufacturing, assembly, or quasi-static errors. The rotary axis in a common five-axis machine tool is driven by a single motor that holds the platform for axial rotation. However, with different weights of workpieces and motor loaded, the rotating speed should be inversely proportional to the weight. Hence, the axis-to-axis synchronization is poor, resulting in a considerable reduction in machining precision. Therefore, a 2PRP planar parallel platform is designed by connecting two PRP connectors and a moving table with a round bar. The motor drives ball screws and propels these PRP connectors. The two parallel ball screws affect both movement and rotation by generating different displacements of these two connectors. Parallel to the advances in hardware design, the programming requirements of machines have increased in complexity, and a nimiety of computer-aided systems collectively are now utilized to manufacture extremely complex machine components.

Compared with serial kinematic machine tools, parallel structured machine tools offer many advantages such as compact structure and higher structural rigidity; they also exhibit a considerably higher load-bearing capacity; parallel structures are not easily bent or changed. Another advantage can be the reduction of dynamic errors through the prevention of error accumulation, thus yielding high precision. Implementation with availability of modular design and assembly, simple structure, and small inertia is achievable. Because the flow of force through structures is short, the effect of thermal expansion is reduced in symmetric structures. Determining joint coordinates as functions of the tool tip position by inverse kinematics is considerably easier.

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Table 1
A brief comparison between parallel and serial mechanisms.

Item	Parallel mechanism	Serial mechanism
Working-space	Limited	Expected
Modular design/Structure	Simple	Stack-up
Effect thermal expansion	Small(symmetry structure)	More
Flow of force	Short	Long
Forward kinematics solution	Very difficult	Easy
Inverse kinematics solution	Easy	Difficult
Position error	Averages	Accumulates
Dynamic error	Accumulates	Averages
Maximum force	Resultant of all actuators	Limited by minimum actuator
Rigidity/Stiffness	High	Low
Structure	Simple	Stack-up
Modal analysis	Very complex	Relatively simple
Inertia	Small	Large
Workspace/footprint ratio	Low	High
Load-bearing/weight ratio	High	Low
Speed and acceleration	Relatively high	Low
Accuracy	Relatively high	Low
Uniformity of components	Relatively high	Low
Calibration	Complicated	Relatively easy
Dynamics characteristics	Superior	Poor

Parallel mechanisms are often more precise than serial robots because they do not incur error accumulation. Although this might be true in theory [1], the actual reason is that parallel robots can be constructed to be stiffer without being larger. Most precision positioning prototypes based on planar parallel mechanisms depend on the use of flexures [2]. Among the few existing planar 3–degree of freedom (DOF) parallel mechanism prototypes that do not employ flexures, one prototype is based on symmetric 3-PRP architecture, where the base actuators form an equilateral triangle and the platform linear guides form a star. However, this robot has an extremely limited work space. By contrast, the 3-RRP mechanism, of which a new prototype was proposed in [3], offers unlimited rotation in addition to excellent stiffness in the vertical direction [4]. Another triangular platform has 3-PRR kinematic structure which consists of one prismatic, two revolute joints is used in [5] as a compliant mechanism. Mechanical kinematics is typically divided into two categories: direct and inverse kinematics. In inverse kinematics, the location of an end effector is provided, and the objective is to determine joint variables. Contrarily, in direct kinematics, the joint variables are provided, and the objective is to determine the position of the end effector [6–10].

In many characteristics and practices, PKMs and serial machines are the opposites of each other. Fully PKMs have relatively very limited working-space, especially in terms of orientation characteristics. Fully serial machines have a problem of axis stack-up, and therefore suffer from error accumulation. From the above descriptions, Table 1 provides some features between serial and parallel mechanisms [11,12].

Because of the simultaneous interpolation movement on both the linear and rotary axes on a five-axis machine, the derivation of the five-axis feeding path is more complex than that of the three-axis feeding path. Therefore, a postprocessor must be used to convert cutter location (CL) data in a computer-aided manufacturing (CAM) system into machine control data. Although advanced controllers can accept CL data to machine a workpiece in real time without a postprocessor [13], they are relatively expensive and used only in specific processes. The methods of developing multi-axis postprocessors can be mainly divided into three categories: graphical [14], numerical iterative [15], and coordinate transformation [16–18]. The coordinate transformation method leads to the analytical equation of NC data most efficiently and has been used regularly in recent studies. Therefore, almost all of these methods involve postprocessors for five-axis machine tools with orthogonal rotary axes. Sorby [19] provided a closed-form solution for a table-tilting type five-axis machine tool with a nutating table. However, only few studies have addressed the nonorthogonal configuration for translation or rotary axes. Another example is a spindle-tilting type five-axis machine tool with a nutating head [20]. The postprocessor may be positioned as shown in the flowchart in Fig. 1, which illustrates the concept that the postprocessor is not only a part of the CAM system but can also be a stand-alone system.

The remainder of this paper is organized as follows. Section 2 describes the hybrid five-axis machine tool and homogeneous transformation. The construction of the forward and inverse kinematics by using a mathematical model is presented in Section 3. Section 4 presents the establishment of the postprocessor system to convert CL data into the NC codes. Section 5 illustrates three machining samples to demonstrate the feasibility of the proposed method. Finally, Section 6 concludes this paper.

2. Hybrid five-axis machine tool

Understanding the complexity of CNC and their applications requires knowledge of mechanical engineering, electrical engineering, manufacturing engineering, software engineering, computer science and economics. It is really not easy to declare what kind of mechanism is better, serial or parallel. Table 1 provides a short comparison of essential considerations between parallel and serial mechanisms [11]. A mechanism differentiation procedure is complicate and difficult. It depends on various factors, especially which task requirements are causing the workpiece performance.

PKMs, possess superior mechanical characteristics to serial structures, were supposed to have the potential to form a basis for a new CNC-type to challenge traditional machining centers. Nevertheless this idea has faded out as some problems still remain and could not be solved completely. Fully parallel mechanisms with five degrees of freedom have comparatively very small working-space. To improve this restriction, the CNC was designed as a hybrid configuration in this paper. Resemble the serial kinematic design, most of the hybrid kinematic designs are designed the first three links and joints, forming the parallel structure, control the translational positioning of the spindle. The rest of joints and links are made to form a concurrent serial kinematic structure to rotate the spindle equipped on the parallel platform [21]. An asymmetric hybrid structure for small 5-axis motion platform was proposed in [22]. Recently a hybrid structure with the parallel platform and the tilt rotary table was present in [23]. This paper proposed a very different type of hybrid 5-axis machine tool which is very suitable for symmetric workpieces [24].

On simplification, a machine tool may be considered a set of links joined in a set of connectors. A five-axis machine coordinate frame conventionally comprises the X, Y, and Z axes in the right-hand rectangular coordinates. The rotary axes are defined as A, B, and C, and they rotate about the X, Y, and Z axes, respectively. The common configuration of five-axis machine tools can be classified into three basic types [25]: (1) double rotary table, which comprises two rotations on the table; (2) double pivot spindle head, which comprise two rotations on the spindle; and (3) rotary table and pivoting spindle head, which comprises one rotation each on the table and spindle. The tools can be designated according to the features of the rotary axes such as AB, AC, and BC types. Each type has two appropriate cutter orientations to support the five-axis machining function. Basically, the cutter orientation is defined as the Z axis, and the five-axis machine tools can be classified as the AB, AC, and BC types.

A five-axis CNC machine tool requires at least five actuators. Under the consideration of additional costs, a machine is related to the number of actuators, the structure of a hybrid five-axis machine tool with five actuators provides an apparent potential advantage over the hexapod. Fully serial structures and fully parallel structures do not belong to hybrid structures, these two structures were eliminated from consideration in this paper. Some different combinations of axis configuration for five-axis CNC machine tools are possible to build up, as shown in Tables 2 and 3. Basically, here are three possible candidates to form five-axis ma-