Design and experimental study of the SPKM165, a five-axis serial-parallel kinematic milling machine

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A five-axis serial-parallel kinematic milling machine, the SPKM 165, is introduced. This machine consists of a three-degree-of-freedom parallel module and a two-degree-of-freedom serial table. The SPKM 165 is capable of five-face machining. A discussion of the inverse kinematics of the five-axis control is provided. A dimensional synthesis procedure is presented in terms of motion/force transmissibility. Finite-element analysis was used to evaluate the stiffness of a CAD model before the machine was manufactured. Kinematic calibration was implemented to improve the accuracy of the end effector. The results of a calibration experiment are presented. The stiffness of the developed machine was then measured. Milling experiments were conducted, and the test piece showed that the developed machine has satisfactory performance.

1 Introduction

Parallel kinematic mechanisms (PKMs) have been studied for more than twenty years. Compared with serial kinematic mechanisms (SKMs), PKMs have a more compact structure, a lower moving inertia, higher stiffness, and a higher load-to-weight ratio. The Stewart platform revolutionized the field of machining when it first emerged as a possible configuration for a machine tool [1]. The highly successful Delta robot similarly improved the packing industry. Hereafter, PKMs are seen as the next industrial innovation, and are claimed to be the next generation of machine tools. Indeed, PKMs outperform SKMs in terms of surface finish and geometric accuracy when cutting hardened materials [2].

The disadvantages of PKMs include limited workspace and low dexterous manipulation [3]. Other drawbacks include the complex solutions to forward kinematics, coupling between the rotation and position capabilities, and geometrically complex workspaces. These disadvantages complicate the control and calibration of PKMs. Therefore, PKMs have not developed as expected.

Redundant PKMs take advantage of redundancy to avoid singularity, to improve dexterity [4], to achieve a uniform workspace, and to enlarge the linear or angular working volume for a given footprint. However, whether such mechanisms are suitable for machine tools should be further investigated.

SKMs provide a relatively large and regular workspace, high flexibility, and simple solutions to forward kinematics. SKMs and PKMs are limited in their applications, although both provide different advantages. Creating serial-parallel kinematic mechanisms (SPKMs) by adding a serial table to the parallel module might increase manipulability and workspace. SPKMs can combine the benefits of both PKMs and SKMs.
and SKMs while avoiding the drawbacks of either. Such a configuration might be ideal for machine tools. SPKMs allow a flexible axis arrangement, moderate complexity, and reasonable technological risks. All of these make SPKMs a viable concept for machine tools, and as such have received considerable attention [1, 5–11]. Five-degree-of-freedom (DOF) SPKMs, incorporating one three-DOF PKM and one two-DOF SKM, are especially popular.

Three-DOF PKMs are popular because they are easier to use as machining modules. This is due to their simple kinematics and uncoupled or partly uncoupled motions [12–18]. Some of these, such as the Space 5H tool head [19] and the Sprint Z3 tool head [20], have been successful.

Five axes (i.e., three translations and two rotations) are typically required for five-face machining. A high orientation capability of the machine tool is needed as well. To this end, a parallel module with high orientation capability is the key problem. In our former work, such a parallel mechanism has been proposed [21]. By using this mechanism, a prototype of the five-axis SPKM 165 is presented in this paper. This machine is composed of one three-DOF PKM and one two-DOF serial table. The rotational ability of the three-DOF PKM is up to 110°. Due to this capability, the SPKM 165 can alternate between a vertical and a horizontal configuration, which allows five-face machining with the cooperation of the serial table.

The optimal design of PKMs is one of the most important problems to be solved [13, 22–24]. There are two issues involved: performance evaluation and dimensional synthesis. The first problem is the most important. The local conditioning index (LCI) [25], although popular, will not be used in this paper. A new index based on transmission angle [26] will be suggested to evaluate motion/force transmissibility. The second problem is determining the link lengths of the mechanism, which are fundamental to the design of the machine.

Precision is an important factor for engineering applications, especially for machine tools [27]. An analysis of the stiffness of a prototype is necessary prior to the manufacture of the machine. This is because stiffness greatly influences precision and the surface finish. The matrix stiffness method [28–31] and the finite-element method (FEM) are the most commonly used methods for stiffness analysis. The FEM is effective in evaluating the performance of a parallel or hybrid machine under actual working conditions. This method can precisely evaluate the static stiffness of a machine as well as simulate deformation and stress. Stiffness evaluation in this paper is conducted by using commercial software based on finite-element analysis (FEA). Kinematic calibration which provides an effective solution [32, 33] is used in this study to further improve accuracy after the prototype is manufactured. There are four steps to kinematic calibration: error modeling, measurement, parameter identification, and error compensation. Parameter identification is important since the identification method varies according to the characteristics of the mechanism to be calibrated. A new identification method was recently proposed by our team [34]. This method was used in the calibration of this prototype.

This paper is organized as follows. Section 2 introduces the structure of the prototype and its inverse kinematics. The dimension determination of the parallel module and the CAD model of the machine are presented in Section 3. Section 4 introduces the stiffness evaluation of the designed model. The developed machine is described in Section 5. Kinematic calibration is discussed in Section 6, where the experimental results are given. Stiffness measurements and milling experiments are presented in Section 7. Conclusions are given in Section 8.

2 Configuration and inverse kinematics

2.1 Configuration description

The SPKM used for the prototype is composed of a three-DOF parallel module and a two-DOF serial table. The parallel module is called HALF*, which was introduced in ref. [21]. As shown in Figures 1(a) and 1(b), the mobile plat-