Mechanism and Machine Theory 71 (2014) 142–162

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Performance enhancement of a three-degree-of-freedom parallel tool head via actuation redundancy

Wang Dan *, Fan Rui, Chen Wuyi

School of Mechanical Engineering & Automation, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 14 May 2013
Received in revised form 16 September 2013
Accepted 19 September 2013
Available online 17 October 2013

Keywords:
Parallel manipulator
Hybrid machine tool
Actuation redundancy
Dexterity
Stiffness

ABSTRACT

This paper presents a novel type of three degree-of-freedom (DOF) redundant parallel tool head (PTH) which is developed by introducing actuation redundancy to an originally designed non-redundant 3-DOF PTH. To diminish the physical constraints imposed by spherical joints, a modified spherical joint with large tilting capacity is introduced. The two types of PTHs, the redundant form and the non-redundant one, are then fully compared with each other in terms of singularity distribution, workspace shape, kinematic performance and stiffness behavior. The comparison results show that the redundant PTH has several notable advantages over the non-redundant one, including enlarged singularity-free workspace, improved dexterity performance and higher stiffness.

1. Introduction

Parallel kinematic machines (PKMs), if properly designed, can provide considerable advantages over their serial counterparts in terms of high stiffness, high accuracy and low inertia. Due to these virtues, PKMs are suitable candidates for high-speed and high-precision machine tools, especially for those designed for high-hardness materials' machining. The early stage PKM-based machine tools were mainly designed in fully parallel forms [1] and could hardly be used for 5-axis complex surface machining because of problems such as small workspace, small tilting capacity and bundles of configuration singularities in the workspace [2–4].

To enlarge the tilting capacity and workspace volume of the PKM, many researches have been focused on the hybrid machine tools (HMTs). Many practical 5-DOF hybrid solutions had been proposed, which were mainly realized either by adding a 2-DOF serial spherical wrist to a 3-DOF PKMs such as the Tricept robot [5,6], Exechon machine tool [7] and Trivariant robot [8–10], or by combining a 3-DOF PTH to a 2-DOF serial translational platform [11–13], e.g. the DS Ecospeed machine tool. However, since every coin has two sides, there still exist some drawbacks to the HMTs, e.g. the DS Ecospeed machine tool with Sprint Z3 head only has a maximum tilting angle of ±40° [1], which is hardly possible to meet the demands in practical machining of aerospace parts such as impeller and blisk. Furthermore, manipulator singularities are still inherent limitations to the manufacturing capabilities of the HMTs. Nevertheless, actuation redundancy is a potential to diminish these problems. In literatures, actuation redundancy had been proved to be an effective way to eliminate singularities and to improve the stiffness of a PKM [14–17]. In addition, the usable workspace of a HMT can also be increased by the elimination of configuration singularities.

In this paper, based on a 3-DOF non-redundant PTH, a 3-DOF PTH with actuation redundancy is developed by introducing an additional leg with active actuator. The two types of PTHs, i.e. the non-redundant PTH and the redundant one, are fully compared with each other in terms of singularity distribution, workspace size, kinematic performance and stiffness behavior.

---

* Corresponding author. Tel.: +86 01082317471.
E-mail address: wangpick@gmail.com (D. Wang).

0094-114X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mechmachtheory.2013.09.006

The paper is organized as follows: in Section 2, the two types of PTH are introduced and their geometric models are shown. In Section 3, kinematic analysis of the PTH is performed and Jacobian matrix is generated. In Section 4, singularity distributions of the two types of PTH are compared in the entire orientation workspace on the basis of Jacobian analysis. In Section 5, reachable workspaces are generated. The dexterity behavior and the stiffness performance are then analyzed in Sections 6 and 7, respectively. Finally, the conclusion to this paper is given.

2. Architectural description

2.1. Architectures of the 3-DOF PTH

As shown in Fig. 1(a), the basic form of the proposed PTH is developed on basis of a 3-PRS parallel mechanism. The basic form of the PTH consists of a swivel table, a fixed frame, three identical prismatic–revolute–spherical (PRS) kinematic legs and a machine tool spindle. The three PRS legs are arranged in 120° intervals on the guide ways and each leg connects the swivel table to the fixed base with a modified spherical (S) joint followed by a revolute (R) joint and a prismatic (P) joint in sequence, where P joint is the active joint. The modified S joint is mounted at one end of the PRS leg and connected to the swivel table while the P joint is fitted to the other end of the PRS leg. In practice, each P joint is composed of a slider, a lead screw and a pair of sliding rails. The P joint is connected to the fixed frame of the PTH through the two sliding rails and the R joint of the PRS leg is mounted on the slider. The P joint is driven by a linear actuator which is implemented by a lead screw actuation system driven by an alternating current (AC) servo motor. A machine tool spindle, covered by a spindle hood, is installed on the swivel table of the 3-DOF swivel tool head.

As shown in Fig. 1(b), the redundant form of the PTH is obtained by mounting an additional leg between the fixed frame and the swivel table of the basic form. The additional leg connects the spindle hood to the fixed base with a modified S joint, a P joint and a universal (U) joint in sequence. Concretely, The S joint is mounted at one end of the UPS leg and connected to the spindle hood fixed on the swivel table while the U joint is installed on the fixed frame and at the other end of the UPS leg; the P joint is an active joint and driven by a cylindrical lead screw actuation system. At the home position, the central axis of the UPS is parallel to the three sliding rails of PRS legs with the U joint mounted at the center of the fixed frame. The connectivity of the universal–prismatic–spherical (UPS) leg is equal to six. Therefore, it provides no constraint on the swivel table, which ensures that the redundant form of the PTH has the same mobility with the basic form.

The representation of the vectors and joints of the proposed PTH is depicted in Fig. 2. Three sliding rails intersect the fixed frame at points $A_i (i = 1, 2, 3)$ which lie on a circle of radius r_a. Three kinematic legs C_iB_i for $i = 1, 2$ and 3 with length l connect the swivel table at points $B_i (i = 1, 2, 3)$ which lie on a circle of radius r_b and are respectively the central points of the three S joints. Points C_i indicate the position of the ith R joint on the corresponding sliding rail. A fixed Cartesian reference coordinate frame $O(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$ is set at the central point O of the fixed frame $A_1A_2A_3$, while a moving reference frame $P(\boldsymbol{u}, \boldsymbol{v}, \boldsymbol{w})$ is attached on the swivel table $B_1B_2B_3$ at the central point P. Without losing the generality, let the $\mathbf{x}$-axis point in the direction of vector OA_3 and the $\boldsymbol{u}$-axis point along vector PB_3. In the x–y plane $A_1A_2A_3$ and the u–v plane $B_1B_2B_3$, vectors $\boldsymbol{a}_i$ and $\boldsymbol{b}_i$ denote the vector OA_i in the fixed frame $O(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$ and vector PB_i in the moving reference frame $P(\boldsymbol{u}, \boldsymbol{v}, \boldsymbol{w})$, respectively. In Fig. 2, $\boldsymbol{l_i}$ $(i = 1, 2, 3)$ denotes the vector from C_i to B_i and $\boldsymbol{d_i}$ $(i = 1, 2, 3)$ is the vector from A_i to C_i. In practice, the UPS leg is mounted between point O and point B_4 which is the central point of the 4th S joint, vector $\boldsymbol{d_4}$ is the vector from O to B_4.

To simplify the calculation, the $\boldsymbol{x}$-axis of the fixed frame $O(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$ lies in the fixed frame plane $A_1A_2A_3$ and through the point A_3; the $\boldsymbol{y}$-axis also lies in the plane $A_1A_2A_3$ while $\mathbf{z}$-axis is normal to the plane $A_1A_2A_3$, pointing downward. For the moving frame

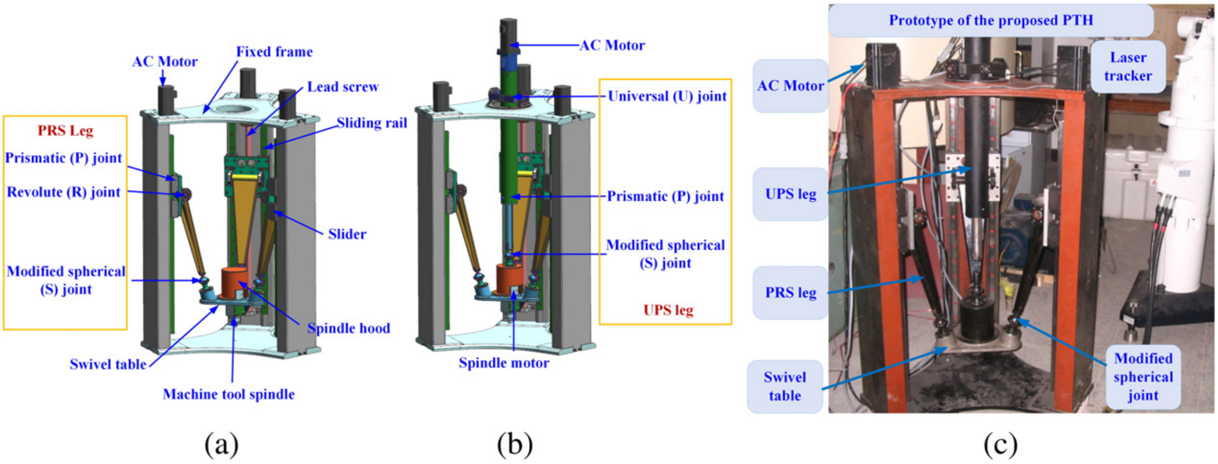

Fig. 1. Architecture overview of the 3-DOF PTH. (a) the basic form, (b) the one with actuation redundancy and (c) the prototype of the PTH.