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Dynamic modeling and redundant force optimization of a 2-DOF parallel kinematic machine with kinematic redundancy

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ABSTRACT

High precision is still one of the challenges when parallel kinematic machines are applied to advanced equipment. In this paper, a novel planar 2-DOF parallel kinematic machine with kinematic redundancy is proposed and a method for redundant force optimization is presented to improve the precision of the machine. The inverse kinematics is derived, and the dynamic model is modeled with the Newton–Euler method. The deformations of the kinematic chains are calculated and their relationship with kinematic error of the machine is established. Then the size and direction of the redundant force acting on the platform are optimized to minimize the position error of the machine. The dynamic performance of the kinematically redundant machine is simulated and compared with its two corresponding counterparts, one is redundantly actuated and the other is non-redundant. The proposed kinematically redundant machine possesses the highest position precision during the motion process and is applied to develop a precision planar mobile platform as an application example. The method is general and suitable for the dynamic modeling and redundant force optimization of other redundant parallel kinematic machines.

1. Introduction

Parallel kinematic machines (PKMs) possess many advantages compared with those serial machines, including better dynamic performance, higher stiffness, larger payload capacity and higher modularization degree [1–3]. Owing to these merits, they have already aroused great attention and been widely applied to different fields [4]. However, PKMs also suffer from relatively small useful workspace, complex and excessive singularities, and vibrations of kinematic chains [5,6].

Redundancy is considered to be an effective way to conquer these issues. It can in particular reduce or even eliminate singularities [7,8], enhance stiffness and improve precision [9,10]. There are three general categories for adding redundancy [11,12]. The first is replacing the passive joints with actuators, the second is adding additional kinematic chains, and the last is the combination of the first two categories. Redundancy in PKMs introduced by the above mentioned methods can be divided into two different types: (a) Actuation redundancy and (b) kinematic redundancy [13].

The development of machine tools has called for the excellent dynamic characteristic of the PKMs, especially when high speed and large cutting forces are required [14]. The introduction of redundancy in PKMs can be deemed a promising approach to improve their dynamic properties. To this end, the optimal control of redundant forces is one of the key problems. The accuracy dynamic model should be established at first, which is the basis of determining the redundant forces reasonably [15]. The popular dynamic modeling methods for a PKM mainly include the Newton–Euler method [16–18], the Lagrange method [19–21], the principle of virtual work [22,23], the screw theory method [24] and the Kane equation. [25,26]. Nevertheless, infinite solutions will be obtained when these methods are used in the dynamic modeling of a redundant PKM. To solve such a problem, a cost function should be defined on goals, such as minimizing the potential energy [27,28], improving the force transmission performance [29], enhancing rigidity [30], reducing the internal forces of joints [31] and so on. All these methods can provide appropriate supplementary conditions for solving the dynamic model, and improve the dynamic performance of the machine. But there is no literature involved with minimizing the position errors of the manipulated platform, which is crucial in advanced PKMs. Furthermore, the kinematic chains of PKMs are generally elongated rods, so they are easy to deform especially under larger external loads. It will deteriorate the precision of the machine [32,33]. So it is necessary to improve the precision by optimizing the redundant force in a redundant PKM.

Although redundancy has been investigated in PKMs to improve their dynamic performance before, the majority of these works concentrated on actuation redundancy [34,35]. There are few references that deal with the introduction of kinematic redundancy for a

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PKM. And the studies of the advantages of adding kinematic redundancy were avoiding kinematic singularities, increasing workspace, and improving dexterity [36]. The motion of redundantly actuated kinematic chain is determined by other moving parts, so it is only permitted to control the size of the redundant force. However, kinematically redundant kinematic chain can control both the size and direction of the redundant force. Theoretically, a better effect in improving the dynamic performance of the machine can be obtained.

As shown in Fig. 1, a 4-DOF heavy hybrid machine tool [14] is created by combining a 2-DOF PKM with actuation redundancy and a work table. The running precision of the redundantly actuated PKM can be improved through optimization of the redundant force at an extent. In some cases, such as the running trajectory close to the workspace boundary, however, it is difficult for the actuation redundancy to compensate the position errors of the machine [37]. In this paper, a kinematically redundant kinematic chain is introduced and a novel planar 2-DOF PKM with kinematic redundancy is proposed. The size and direction of the redundant force are optimized to improve the precision of the machine. The remainder of this paper is organized as follows. In the next section, the inverse kinematics of this machine is analyzed. Then its dynamic model is constructed in Section 3. In Section 4, the deformations of the links are calculated and their relationship with the kinematic errors of the manipulated platform is deduced. Then the errors are minimized by optimizing the size and direction of the redundant force. In Section 5, the dynamic performance of this machine and its two counterparts are compared by numerical simulations to verify the effectiveness of this method. A precision planar mobile platform is created based on the structure of the 2-DOF PKM with kinematic redundancy as an application example. Finally, conclusions of this paper are given.

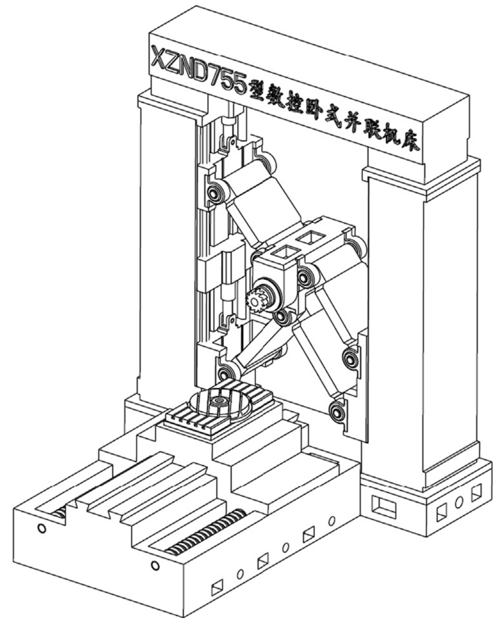

Fig. 1. 4-DOF hybrid machine tool.

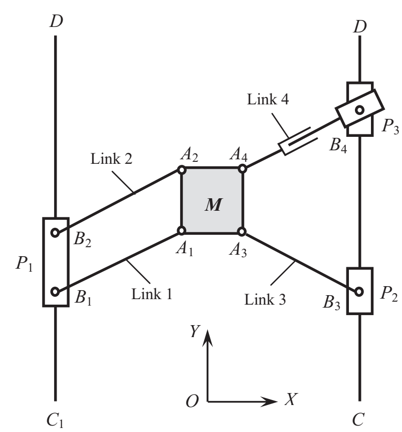

Fig. 2. Schematic diagram of the machine.

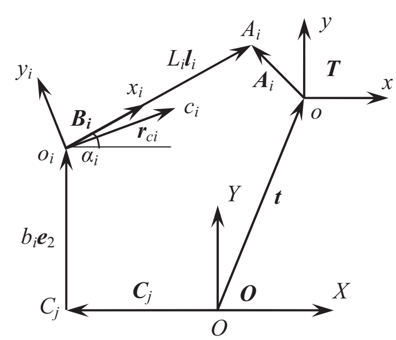

Fig. 3. Vector loop of a kinematic chain.

2. Inverse kinematics

2.1. Description of the kinematically redundant PKM

As shown in Fig. 2, the 2-DOF PKM is composed of a manipulated platform, two vertical rails, three active sliders, three identical links and an extensible link. The extensible link consists of two members connected by a prismatic joint. Sliders P_1, P_2 and P_4 drive links A_1B_1, A_2B_2, A_3B_3 and A_4B_4 when they move along the vertical rails, and the sliders are driven by the servo motors via ball screw. There exists a parallelogram mechanism, which limits the rotation of the manipulated platform. So the manipulated platform possesses two translational degrees of freedom. Thus, the machine is kinematically redundant since it has four actuators and the actuator–displacement of slider P_3 has infinite choices in the execution of a given task.

2.2. Inverse kinematics

As illustrated in Fig. 3, a reference coordinate frame $\{\boldsymbol{O}\}: O-XYZ$ is located at the midpoint of C_1C_2, a moving coordinate frame $\{\boldsymbol{T}\}: o-xyz$ is attached to the manipulated platform at its central point, and another moving coordinate frame $\{\boldsymbol{B_i}\}: o_i-x_iy_iz_i$ is attached to link A_iB_i at point B_i.

According to Fig. 3, the kinematic constrained equation of the ith kinematic chain can be written as

$$\boldsymbol{t}+\boldsymbol{A}_i=\boldsymbol{C}_j+b_i\boldsymbol{e}_2+L_i\boldsymbol{l}_i \quad (i=1,2,3) \tag{1}$$

where $\boldsymbol{t}=[x,y,0]^{\mathrm{T}}$, $\boldsymbol{A}_i=[x_{Ai}, \ y_{Ai}, \ 0]^{\mathrm{T}}$ and $\boldsymbol{C}_j=[x_{Cj},y_{Cj},0]^{\mathrm{T}}$ $(j=1,2)$ are the position vectors of points T, A_i and C_j in $\{\boldsymbol{O}\}: O-XYZ$, respectively. Besides, $\boldsymbol{e}_2=[0,1,0]^{\mathrm{T}}$ is the unit vector of vertical rail, and b_i is the distance between points B_i and C_j. L_i and $\boldsymbol{l}_i$ denote the length and unit vector of linkA_iB_i.

The solutions of the inverse kinematics can be written as

$$b_i=y+y_{Ai}-y_{Cj}\pm\sqrt{L^2-(x+x_{Ai}-x_{Cj})^2} \tag{2}$$

From Eq. (2), we can see that there are eight solutions for the inverse kinematics of this machine. The eight solutions correspond to eight kinds of working modes. For the configuration shown in Fig. 2, all the "$\pm$" in Eq. (2) is "$-$".