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Dynamic analysis and driving force optimization of a 5-DOF parallel manipulator with redundant actuation

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ABSTRACT

Redundant actuation can improve the performance and ability of parallel manipulator. In order to deal with coordination and distribution of the driving force of the parallel manipulator with redundant actuation and to realize the control strategy based on dynamics, on the basis of the original 5UPS/PRPU parallel manipulator, it increases a drive for the middle PRPU passive constraint branch to make it a redundant actuation branch. It introduces configurations' redundant types and compositions of 5UPS/PRPU parallel manipulator with redundant actuation, illustrates that the mechanism is redundant actuation from the perspective of degree of freedom and establishes a dynamic model based on Lagrangian method. On the basis of the weighted optimization principle of driving torque, it optimizes the driving torque of the parallel manipulator and calculates the driving force of the redundant driving chain with cutting force. It carries out the simulation by using ADAMS software and proves validity of dynamic model. Finally it detects the dynamic performance of the parallel manipulator by processing experiment of parallel manipulator with redundant actuation and its non-redundant counterpart.

1. Introduction

Parallel mechanism with redundant actuation is a mechanism whose number of drives in the system is larger than that of independent motion joints. This kind of mechanism can eliminate the singularities [1,2], increase the working space, reduce the instantaneous maximum load, improve the precision [3] and the load capacity [4], enhance stiffness [5]and so on. At present, the research on redundant actuation is mainly focused on overcoming the singularities, and thus increases the effective working space. However, the theoretical research and experimental verification on the coordination and distribution of the driving forces of different branches by using redundant actuation are very rare. The improper distribution of the driving forces can affect its function practice and even destroy the equipment because of the excessive inner force. Nahon and Angeles [6] summarized three kinds of methods to solve the optimal force distribution problem of redundantly actuated parallel manipulator, which are based on Lagrange multiplier, weighted pseudo-inverse and direct substitution respectively. Zhang Yanfei et al. [7]studied the theory of singularity elimination by redundant actuation for parallel mechanism. Yang Yang et al. [8]put forward a novel space 2 T parallel manipulator with redundant actuation, carried out the dynamic analysis and optimized the driving force by using the least 2-norm criterion. Gao et al. [9,10]analyzed the kinematics and dynamics of a 6-DOF 8PSS redundant parallel manipulator and obtained the optimal solution of the output of each branch by using the Moore-Penrose inverse matrix. Wu et al. [11]derived the inverse dynamic model of a planar 3-DOF parallel manipulator with redundant actuation, and the driving force was optimized by using the least square method. Wang et al. [12]studied the dynamics of a planar 2-DOF parallel mechanism with redundant actuation and the redundant driving force optimization was performed while taking the minimum position error as the optimization objective. Xu et al. [13]analyzed the inverse dynamics and the internal force of the redundant actuation parallel mechanism by means of the deformation coordination equation. João Vitor Fontes and Maíra Martins da Silva [14] considered two strategies to assess the impact of kinematic and actuation redundancies on the dynamic performance of planar parallel kinematic manipulators. Seoul National University, South Korea developed a five-face fast processing parallel machine tool Eclipse with redundant actuation. Regarding the progress of 5-DOF parallel manipulators, Zhu et al. [15]studied the singularity for six practicable 5-DOF 3R2T fully-symmetrical parallel

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manipulators. Sun et al. [16] investigated a novel 5-axis hybrid reconfigurable robot named Tricept-IV and demonstrated a method of workspace decomposition based dimensional synthesis of the robot. Saadatzi et al. [17] investigated the constant-orientation workspace of 5-DOF parallel mechanisms. Lian et al. [18] proposed a novel 5-DOF parallel kinematic machine and established the semi-analytical theoretical stiffness model considering gravitational effects. Taking a 5-DOF manipulator (T5 PM) as an example, Lian et al. [19] carried out parameter sensitivity analysis with respect to the mass and stiffness performance based on response surface method and performance reliability. etc.

The dynamic research of the parallel manipulator with redundant actuation is the theoretical basis of the whole machine dynamic design, the driving force optimization, the driving force coordination and the control. According to different mechanical principles, there are many theoretical methods in the research of mechanism dynamics. For example, Newton-Eular [20–24]method which derives the dynamics of rigid body by using the inertia force of the object based on the Newton's law and Euler's dynamic equation. Kane [25–29]method which avoids the analysis of constrained internal forces and the solution of partial differential equation, uses the partial velocity, angular velocity, generalized velocity, generalized active force and generalized inertial to establish the dynamic model. Lagrange [30–35]method uses generalized coordinate, work and energy to establish dynamic model of parallel manipulator; its equation number is equal to the degree of freedom of the parallel manipulator. In modeling, there is no need to analyze the constrained internal force of the mechanism, but only to analyze active driving force of the parallel manipulator. Virtual work method [36–41] establishes dynamic model according to the theory that the work in any virtual displacement of the active force acting on the ideal system is zero. In addition, Song et al. [42] carried out the elasto-dynamic analysis of a novel 2-DOF rotational parallel mechanism (RPM) with an articulated travelling platform by means of kineto-elasto dynamic method and validated its effectiveness by means of software simulation. Through the comparison of the above theories on dynamic, Lagrange method is a dynamic modeling method which is suitable for complex systems. It starts from the energy point of view. What is more, the derivation process of this method is simple and the form of the dynamic equation is relatively simple. So it is more suitable for the establishment of dynamic model of the parallel manipulator with redundant actuation.

In order to deeply study the intrinsic connection between redundant driving force and coordination of all the driving forces of the 5-DOF parallel manipulator with redundant actuation, and to realize the hybrid force/ position control based on dynamics, in this paper, the Lagrange method is used to establish the dynamic model. It is based on the weighted optimization principle of driving torque to optimize the driving torque of the parallel manipulator and calculates the driving force of the redundant driving chain with cutting force. By using ADAMS software, it simulates the driving force and carries out the experimental research on redundant actuation. It is of great significance to the further study on the theory and experimental research of redundant actuation.

2. Structure description

2.1. The composition of the parallel manipulator

The redundant actuation 5UPS/PRPU parallel manipulator is composed of a fixed platform, a moving platform, and five branches connecting the fixed platform and the moving platform. The structure is shown in Fig. 1. Its characteristic is that the fixed platform is connected with the moving platform through 5 UPS branches with identical structure and 1 middle PRPU branch.

The middle PRPU branch used to be a constraint branch, only to limit the freedom of moving platform around its own rotation. Now, the first prismatic joint of the constraint branch is added to a drive, which consists of the parallel manipulator with redundant actuation. The position and pose of the moving platform are realized by controlling the movement of the prismatic joints in the 5 UPS branches and the first prismatic joint in the middle PRPU branch.

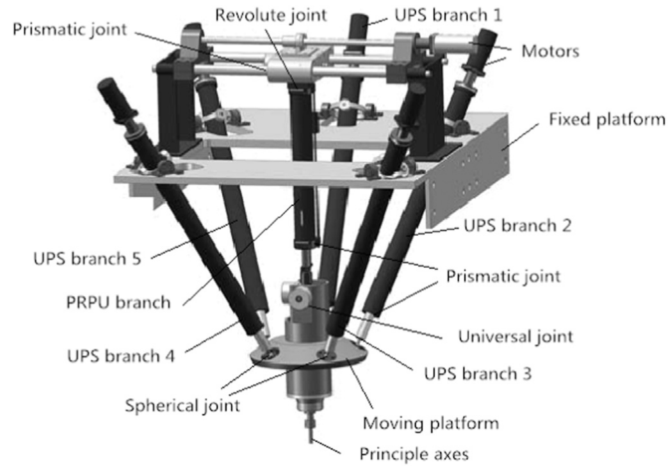

Fig. 1. Virtual prototype of 5UPS/PRPU PMT.

2.2. The analysis on the degree of freedom

The structure of 5UPS/PRPU parallel manipulator with redundant actuation as shown in Fig. 1 is very similar to that of the Stewart platform. The degree of freedom 's formula is analyzed as follows:

$$M = 6(n - g - 1) + \sum_{i=1}^{g} f_i \tag{1}$$

Where M is the number of degrees of freedom, n is the total number of components of mechanism, g is the number of kinematic pairs of mechanism, f_i is the relative degrees of freedom of the i motion pair. Referring to the mechanism shown in Fig. 1, for the 5UPS/PRPU parallel machine tool, n, the total number of components of mechanism is15, the number of kinematic pairs of mechanism g is 19 and the sum of the relative degrees of freedom of kinematic pairs $\sum_{i=1}^{g} f_i$ is 35.

$$M = 6(n - g - 1) + \sum_{i=1}^{g} f_i \quad = 6 \times (15 - 19 - 1) + 35 = 5 \tag{2}$$

According to the formula for calculating the degree of freedom, the degree of freedom of the parallel manipulator with redundant actuation is 5. However, it has 6 active driving branches, so it is necessary to optimize the driving force.

3. Dynamic analysis

Establishing the system dynamic model:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_k}\right) - \frac{\partial L}{\partial q_k} = Q_k (k = 1, 2, \cdots N)$$

Where L is the kinetic energy and potential energy function of the system, q_k is the generalized coordinate of the system, Q_k is the generalized force of the system.

The sum of the kinetic energy of the system is:

$$T = \sum_{i=1}^{3} E_i \tag{3}$$

Where E_1 is the kinetic energy of the moving platform, E_2 is the kinetic energy of 5UPS driving branches, E_3 is the kinetic energy of the middle constraint branch.