Hybrid Force/Position Control Investigation of Parallel Machine Tool with Redundant Actuation

Haitao Tang¹,a, Jiantao Yao¹, Li Cheng² and Yongsheng Zhao¹,b

¹College of Mechanical Engineering, Yanshan University, Qinhuaungdao, Hebei Province, China
²State Key Laboratory of Robotics, Shenyang Institute of Automation, CAS Shenyang, Liaoning Province, China
atht_ysu@163.com, byszhaoyusu.edu.cn

Keywords: PMT; Redundant actuation; Hybrid force/position control; Dynamic performance; Driving force.

Abstract. A novel redundantly actuated parallel machine tool was introduced. The inverse kinematic of 5-UPS/PRPU PMT with redundant actuation was analysed and the driven force of redundant actuation limb was planned. The force/position hybrid control strategy and dynamic differential calculation control strategy were proposed. Then the experiment of evaluating dynamics in the position control mode and in the force/position hybrid control was carried out respectively. The experiment shows that, the force/position hybrid control can improve driven torque of each limb better, balance the load of each limb and is of great help for enhance the dynamic performance of entire PMT.

Introduction

Parallel machine tool is the production of many subjects, including parallel robotics, mechanical manufacturing, computer technology and so on. As a useful complement of conventional NC machine tools, PMT has splendid future in complex surface machining and has been hotly studied in the parallel manipulator and advanced manufacturing field [1-3].

PMT affords a wider space for the development of manufacturing industry, along with the developing direction of advanced manufacturing. However, during the process of becoming practical and commercial, many key problems restricting the development of PMT have appeared gradually: the small workspace and some singular configuration within the workspace; moving platform can get one or more freedoms in the singular configuration, which would weaken the pose control capacity greatly; Around the singular configuration, the stiffness is bad, bearing capacity is low and motion precision is reduced, too. Redundant actuation has became a novel subject in the study field of PMT.

The singular configuration problem can be overcome through redundancy actuation, which can make effective workspace more larger and improve the stiffness and stability, making the velocity, stiffness, precision and bearing capacity more practical.

As a MIMO, nonlinear and strong-coupling system, the motion control of the PMT is extremely complex. Although the dynamic performance of PMT can be improved, it is difficult to realize the redundant actuation, especially the theory research and motion control. As a result, the optimization of internal force of the PMT with redundant actuation is necessary. If the PMT is in the position control mode, the position error and the instantaneous reverse actuation would cause the generation of large internal force between each limb of the PMT, especially in the high-speed and heavy load conditions, excessive internal force may destroy the machine. Consequently, it is suitable to adopt force control or force/position hybrid control in the parallel manipulator tool with redundant actuation [4]. However, the dynamic model should be accurate in the condition of force control, while there is always a difference between the machine in the run and the dynamic model established. As a result, it is hard for the PMT to achieve a high accuracy in the condition of force control. In this paper, a
5-UPS/PRPU PMT with redundant actuation is studied and a force/position hybrid control strategy is proposed, which balances the driven torque of each driver and improves the dynamic performance of the PMT, making the machine achieve a high level of stiffness, accuracy and load capacity.

**Introduction of the PMT with redundant actuation**

In order to improve the PMT performance, the 5-UPS/PRPU parallel manipulator with redundant actuation is based on the original 5-UPS/PRPU parallel manipulator model [5-7]. The redundant actuation is realized by adding the actuation to the passive joint of the constraint limb. The prototype and coordinate system of the 5-UPS/PRPU PMT with redundant actuation is shown in Fig.1.

![Fig.1. The prototype and coordinate system of the 5-UPS/PRPU PMT with redundant actuation](image)

The moving platform and the stationary platform are connected by five UPS limbs and the PRPU limb. The pose of the moving platform can be changed through controlling the expansion of prismatic pair of five UPS limbs and the movement along the guideway of the first prismatic pair of PRPU limb. The number of the motion is 6. The PRPU limb is a passive limb and constrains the rotation of the moving platform around its-self normal axis, making the freedom of PMT is five. Then the 5-UPS/PRPU parallel manipulator with redundant actuation is established.

**Redundant actuation force planning based on kinetics model**

In order to avoid the dynamic calculation of the entire machine, achieve high speed of calculation and meet the need of real-time control for the redundant actuation dynamics, servo control optimization of the redundant actuation limb is conducted: control the driven force of redundant actuation limb to realize the high uniform of the motion of constraint limb in the Z direction and that of moving platform, that is, the mid-limb only constrains the rotation of the moving platform around its-self normal axis and measures the pose of the moving platform in real time. The force along the slide is born by redundant actuation force and the force moving platform applying to the mid-limb in this direction is zero, which wouldn’t cause any burden for other limbs.

The motion of the slider of PRPU limb is simple, which only moves along the Z axis of the fix coordinate system. The dynamic analysis of the middle slider is carried out considering the friction and inertia force. Because of the constraint torque \( M_N \), the slider is subjected to a reacting force along the Y direction of slide. Suppose \( f_{NA} \) and \( f_{NB} \) are equivalent force applied to the two sides; the length of slider is b, then the equivalent force arm is b/3. Suppose the mid-limb moves along the forward Z-axis of reference

![Fig.2. Diagram of the force of the slide of PRPU limb](image)
coordinate, the load of slider is shown in Fig.2. $F_6$ stands for redundant actuation force; $f$, $f_A$, $f_B$ stands for friction respectively; $F_q$ stands for support force slide applied to the slider; $F_{ix}$ ($=F_{ix}'$) and $F_{iz}$ stands for swing lever applied to the slider in the X or Z direction respectively; $M_{iy}$ ($=M_{iy}'$) stands for torque swing lever applied to the slider in the Y direction; $l_x$ stands for force arm of $F_q$ relative to $O$; $\mu$ stands for sliding friction coefficient.

According to D’Alembert principal, the redundant actuation force can be obtained through dynamic balance formula as:

$$F_6 = \mu(F_{ix} + F_{iy} + mg) + F_{iz} + 3\mu M_{iy} / b + ma_z$$

(1)

As the formula above is established on the basis of that the mid limb moves along the forward Z-axis, if the direction was changed, the friction would change its direction consequently. The direction of the friction should be determined according to the velocity of slider, make sure the direction of friction $f$ is always reverse to the slider.

**Motion control strategy**

**Dynamic differential calculation control strategy.** The object of using force control for redundant actuation limb is to make sure that the real internal torque of each limb equals to the torque calculated through dynamic model. In the process of controlling, the driven torque got from redundant actuation torque plan is used as the input of force controller. However, because of the clearance and deformation, as well as the difference between dynamic model and the real model, the driven torque got from dynamic model and the real internal torque of redundant actuation limb are different. As a result, the dynamic differential calculation control strategy is used to conduct the pre-planning...
treatment for the input torque of redundant actuation limb. The control idea is: the driven torque got from dynamic model and the real internal torque got from torque sensor are differential calculated. Then the differential result is used as part of the input torque order next time, that is, the input of redundant actuation limb is the driven torque got from dynamic model at the moment adds the deviation between the driven torque got from dynamic model the moment before and the sensor feedback.

**Force/position hybrid control.** For 5-UPS/PRPU PMT, a control device of redundant actuation limb based on the original hardware “IPC+ PMAC motion controller” is added. Based on NT core multi-application operating system Windows, a modular control system of PMT with redundant actuation is studied with VB.

Based on inverse kinematics and planned driven force of redundant actuation limb, the force/position hybrid control strategy is proposed, which is shown in Fig.3. The five UPS limbs are controlled in the position mode to insure the motion accuracy and the redundant actuation limb is controlled in the force control mode, affording the power for the big slider to move in the horizontal direction. The force measured in the force sensor is used as feedback, forming a closed-loop force control.

**Experiment of dynamic performance evaluation**

In this paper, the translation experiments in the position control mode and in the force/position hybrid control mode are carried out and the two results obtained are compared. In this experiment, through communication control software PANATERM, the real-time torque of each driving motor of host computer can be detected. The geometric path is a circle with the radius of 100mm and the height from tool nose to moving platform is 330 mm. In the fig, abscissa stands for movement time of 40s; ordinate stands for driven torque with unit of newton-mm. As the curve diagram got from experiment is the same as expected, the real-time output torque curves of motor 1 and 2 both in the state of position control and force/position control are given. The output torque of motor measured in the position control mode is shown in Fig.4 and the output torque of motor measured in the position/force hybrid control mode is shown in Fig.5.
Fig.4 and Fig.5 depicts the real-time output torque curves in the position control mode and in the force/position hybrid control mode for 5-UPS/PRPU PMT with redundant actuation respectively. Compared the results, we can get the conclusion that, the output torque peak of motor of UPS1 in the position control mode is higher than that in the force/position hybrid control mode. And the improvement of output torque peak in the force/position hybrid control mode is not obvious, which is occurred in the peak only. In the entire process of movement, it can be seen obviously that, the output torque of UPS1 in the force/position hybrid control mode is decreased within a certain range. For the motor of UPS2, the difference of output torque between the beginning and the last quarter movement circle is not large and the change is not obvious. In the two mid-quarter movement circle, it can be seen that, the output torque peak of motor in the force/position hybrid control mode decreased obviously relative to that in the position control mode, making the entire driven torque is eliminated within 720 N·mm. The output torque peak of other limbs are also decreased correspondingly. Furthermore, the driven force of actuation limb is improved and the dynamic performance is enhanced.

Conclusions

In order to improve the driven torque of each driving limb and enhance dynamic performance of the parallel manipulator tool (PMT), a force/position hybrid control system applied to PMT with redundant actuation was proposed. In this paper, a novel 5-UPS/PRPU PMT with redundant actuation was studied. Based on the inverse kinematics solution and dynamic model built for redundant limb, the force/position hybrid control strategy was proposed and the corresponding control system was developed. The experiment in the position control mode, as well as in the force/position hybrid control mode was carried out respectively and the two results were compared. The result showed that, the creeping phenomenon of the slider of the middle limb of the PMT while non-redundancy actuation can be both eliminated in these two control systems. Compared with position control, the force/position hybrid control can better improve the driven torque of each driving limb and enhance dynamic performance of the PMT effectively, and can afford an available control method for high-speed/high-accuracy control of PMT.

Acknowledgement

The project is supported by the Natural Science Fund of Hebei Province, China (Grant No. E2009000387).

References

[1] R. Neugebauer, M. Schwaar, St. Ihlenfeldt: CIRP Annals-Manufacturing Technology 51(1), 293-296 (2002)
[2] Q., Li, H.B. Yan, Y.B. Zhang: Machine Tool & Hydraulics 35(3), 206-207 (2007), in Chinese.
[3] J.X., Yang, D.W. Yu, L.P Wang, et al.: Machinery Design & Manufacture 31(3), 11-14 (2002), in Chinese.
[4] H. Shen, X.Z. Wu, G.F. Liu, et al.: Acta Automatica Sinica 29(4): 567-572(2003), in Chinese.
[5] Y.S. Zhao, Q.C. Li, K.J. Zheng: Proceedings of the 11th World Congress in Mechanism and Machine Science, Tianjin, China, 1588-1591 (2004)
[6] Y.S. Zhao, J.S. Gao, K.J. Zheng, et al.: Computer Integrated Manufacturing Systems 11(11), 1636-1639 (2005), in Chinese.
[7] L. Cheng, H.B. Wang, Y.S. Zhao: ICIRA 2008, Part I, LNAI 5314: 179-188