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Spindle configuration analysis and optimization considering the deformation in robotic machining applications

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ABSTRACT

Robotic machining is an increasing application due to various advantages of robots such as flexibility, maneuverability and competitive cost. For robotic machining, the machining accuracy is the major concern of current researches. And particular attention is paid to the proper modeling of manipulator stiffness properties, the cutting force estimation and the robot posture optimization. However, through our research, the results demonstrate the spindle configuration largely affects the deformation of the robot end-effector (EE). And it may even account for approximately half of the total deformation for machining applications with the force acting perpendicular to the tool. Furthermore, the closer distance between the tool tip and the EE does not mean that the deformation tends to be smaller. Thus, it is reasonable to consider optimizing the spindle configuration based on the optimal robot posture, thereby exhausting advantages of the robot and further reducing machining errors. In this paper, a spindle configuration analysis and optimization method is presented, aiming at confirming the great influence of the spindle configuration on the deformation of the robot EE and minimizing it. First, a deformation model based on the spindle configuration (SC-based deformation model) is presented, which establishes a mapping between the spindle configuration and the deformation of the robot EE. And it confirms the large effect of the spindle configuration on the deformation of the EE. Then, a complementary stiffness evaluation index (CSEI) is proposed. And it adopts matrix norms to evaluate the influence of the spindle configuration on the complementary stiffness matrix in the SC-based deformation model. Using this index, the proposed SC-based deformation model is simplified for the ODG-JLRB20 robot adopted in this paper. Finally, a spindle configuration optimization model is derived to minimize the simplified SC-based deformation model using an iterative procedure. With this model, the optimal spindle configuration with respect to the EE can be obtained for a specific machining trajectory. Experimental results conducted on the ODG-JLRB20 robot demonstrate the correctness and effectiveness of the present method.

1. Introduction

Traditionally, industrial robots were used mostly for low-accuracy machining applications such as pick-and-place, welding and painting. They are recently being more and more dedicated to a variety of high-accuracy tasks, such as grinding, deburring, drilling and even milling, which have been mainly performed with Computer Numerical Control (CNC) machine tools [1] so far. Compared with conventional CNC machine tools, industrial robots have various advantages such as flexibility, maneuverability, small installation space and large workspace. And the total cost of a robot is 30% less than an equivalent CNC machine tool [2]. Thus, for large complicated workpieces, there is increasing interest to use industrial robots instead of CNC machine tools. However, for industrial robots, the main restraint is the insufficient and posture-dependent stiffness. Generally, the stiffness for six degrees of freedom (DOF) industrial robots is less than $1N/\mu m$ [3,4], while that for CNC machine tools is larger than $50N/\mu m$ [5,6]. As s result, industrial robots are not as accurate as CNC machine tools. They can only reach relatively low accuracy (about 0.7 mm) and repeatability (about 0.2 mm) [7]. These limitations for industrial robots significantly induce machining errors and deteriorate machining accuracy [7,8]. Thus, it is important to optimize these factors in robotic machining applications.

For machining errors generated in the robotic machining processes, they can be divided into static and dynamical deformations, which are induced by cutting forces. For the excessive static deformation, the positioning accuracy of the robot may be deteriorated. For the dynamical deformation, it may lead to poor machining quality and inferior production efficiency [3,9]. Thus, the issue of how to decrease the deformation in robotic machining applications is still being studied.

To solve this issue, many researches have been conducted. For a

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given standard industrial robot to perform machining operations, the deformations of the robot are mainly influenced by the following factors: (1) robot stiffness properties (mainly including robot postures optimization [10] and workpiece placement optimization [2,11]); (2) cutting characteristics (mainly containing analysis of cutting forces [12], evaluation and compensation of deformation [3], and vibration analysis and suppression [4,13]); (3) external axis added to the robot system.

For the first factor, there are already many kinds of optimization methodologies proposed, such as stiffness evaluation indexes, posture and workpiece placement optimization methods. To evaluate the robot stiffness, Salisbury [14] proposed a stiffness model to establish the mapping between each joint deflection and the deformation of the robot EE. And then, Chen and Kao [15] introduced a complementary stiffness matrix into the conventional stiffness model and derived an enhanced stiffness model. However, due to calculation of the inverse Jacobian matrix, the calculation errors of the stiffness models are inevitably introduced. To avoid this issue, Abele et al. [16] derived a compliance model. This model can analyze the stiffness characteristics even if the robot is in singularities. Actually, as the stiffness models arise, many optimization methods on robot posture and workpiece placement have been presented. To optimize the robot posture, Guo et al. [10] proposed a stiffness performance index. By maximizing such index, a robot posture optimization model is further established. To optimize the workpiece placement, Lin et al. [11] proposed a global posture optimization methodology based on kinematic, stiffness and deformation maps drawn by the performance evaluation indexes. Using this methodology, the optimal workpiece placement with respect to the robot can be determined. According to the above optimization methods, the robot stiffness can be maximized.

For the second factor, many researchers have devoted to analyzing the cutting characteristics [17]. To compensate the path deviations of milling robots, Zaeh and Roesch [18] developed a model-based fuzzy controller which contains a real-time stiffness model of the robot. This controller computes the mean cutting force using the stiffness model and derives an increasing vibration amplitude. Then, the force-induced deviations are reduced by 70%. To improve the machining quality of the robotic milling, Matsuoka et al. [12] claimed that the machining accuracy can be increased by decreasing the cutting forces, namely, by decreasing the diameter of the tool and increasing the spindle speed. Based on the analysis of chatter mechanism in the robotic milling process, Pan et al. [19] found that the type of chatter (dynamic deformation) is mode coupling chatter rather than regenerative chatter that always occurred in CNC machine tools. To suppress the vibration of the robot so as to improve the boring quality and efficiency, Guo et al. [4] proposed a novel method which installs the pressure foot at the end of the spindle. By supplying enough friction between the pressure foot and the workpiece, the robot vibration can be completely suppressed. Based on the above researches, it can be found that the cutting characteristics are mainly analyzed aiming to reduce machining errors and improve machining accuracy by compensating the static deformation and suppressing the dynamic deformation.

But for the third factor, it has received little attention in robotic machining applications. Generally, for a given 6 DOF industrial robot to perform machining operations, the tool axis does not coincide in general with the last joint axis of the wrist [20,21], resulting that the spindle configuration changes the position of the tool tip. Actually, for robotic machining, external axis configuration mainly refers to the spindle configuration on the robot EE. And from the perspective of Theorem of Translation of A Force [22], it is generally agreed that the closer spindle configuration to the EE is the better. However, through our research, a totally different result demonstrates that the closer spindle configuration to the EE does not mean that the deformation tends to be smaller. For some robot postures with specific force direction applied on it, the farther spindle configuration away the EE may induce the smaller deformation. And the spindle configuration largely affects the deformation of the EE, which may even account for approximately half of the total deformation for machining applications with the force acting perpendicular to the tool. However, there has not been a proper method to analyze and optimize the spindle configuration so far.

To solve this problem, a spindle configuration analysis and optimization method is presented in this paper, aiming to confirm the great effect of the spindle configuration on the deformation of the robot EE and optimize the spindle configuration. This method consists of three steps. First, a SC-based deformation model is established, which is a mapping between the spindle configuration and the deformation of the robot EE. Using this model, the large effect of the spindle configuration on the deformation of the EE is confirmed. Second, CSEI is proposed based on matrix norms, which is used to evaluate the influence of the spindle configuration on the complementary stiffness matrix in the SC-based deformation model. According to CSEI, the SC-based deformation model is simplified for the ODG-JLRB20 robot adopted in this paper. Finally, by minimizing the simplified SC-based deformation model, a spindle configuration optimization model is proposed using an iterative procedure. And it can be adopted to optimize the spindle configuration for a specific machining trajectory.

The ODG-JLRB20 robot is used as an illustrative example throughout the paper, whose mathematical background including kinematic and stiffness modeling is given in Section 2. Section 3 presents the spindle configuration analysis and optimization method, which contains a deformation model based on the spindle configuration, a complementary stiffness evaluation index and a spindle configuration optimization model. Experiments are conducted in Section 4 to validate the proposed method. And discussions about the possible extensions are presented in Section 5. Finally, Section 6 summarizes the main results and contributions.

2. Mathematical background for ODG-JLRB20 robot

2.1. Kinematic parameterization

The ODG-JLRB20 robot adopted in this paper is a 6 DOF industrial robot. The maximum load of the ODG-JLRB20 robot is 20 kg. And the robot configuration ranges in the joint space are shown in Table A.1 of Appendix A. The modified Denavit Hartenberg (DHm) parameters are adopted to parameterize the robot with a spindle. Here, the spindle configuration in the robot EE coordinate system refers to parameters d_7 and a_7 from the robot EE to the tool centre point (TCP) in the frame 7 (labeling of each frame as shown in Fig. 1).

Considering the maximum load of the ODG-JLRB20 robot, the ranges of parameters d_7 and a_7 are set to be 0 ~ 320 mm. And since their values affect the deformation of the robot EE, the optimal values of parameters d_7 and a_7 remain to be discussed in the following section.

2.2. Kinematic Jacobian

The 6 × 6 Jacobian matrix $\boldsymbol{J}$ [23,24] of the robot relates the joint rates to the twist of the EE, namely:

$$\boldsymbol{t} = \begin{bmatrix} \Delta \boldsymbol{p} \\ \boldsymbol{\omega} \end{bmatrix} = \boldsymbol{J}\Delta\theta \tag{1}$$

where $\boldsymbol{t}$ is the twist of the robot EE, which contains the translational velocity vector $\Delta\boldsymbol{p}$ and the angular velocity vector $\boldsymbol{\omega}$.

The actuated revolute joint rate $\Delta\boldsymbol{\theta}$ is expressed as:

$$\Delta\theta = [\Delta\theta_1, \Delta\theta_2, \Delta\theta_3, \Delta\theta_4, \Delta\theta_5, \Delta\theta_6]^T \tag{2}$$

The analytical expression of kinematic Jacobian matrix is displayed in Eq. A.1 of Appendix A.