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Stiffness-oriented posture optimization in robotic machining applications

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ABSTRACT

Industrial robots have been used in machining applications for their advantages such as their high flexibility and low cost. However, the relatively low stiffness of the robot can seriously affect its positioning accuracy and its machining quality. In this paper, a posture optimization method is presented, aiming at increasing the stiffness of the robot in machining applications. First, a performance index is proposed to evaluate the stiffness of the robot with a given posture after an in-depth study of the relationship between the translational displacement of the robot end effector and the force applied on it. The index is then demonstrated to be a frame invariant. By maximizing the index, a robot posture optimization model is further established and solved by a novel solution method based on the Jacobian matrix. Finally, experimental results achieved on a KUKA KR360-2 robot verify the correctness of the stiffness performance index, and the application of the posture optimization method in a robotic drilling system shows its effectiveness.

1. Introduction

Recently, industrial robots are being more and more widely used in a variety of machining applications, such as drilling, milling and grinding because of their flexibility in performing tasks in a relatively small space, and furthermore, at a lower cost. For example, take drilling, it is an important process in the assembly of aerospace components. Manual drilling is labor-intensive and time-consuming, and furthermore, the quality of the drilled holes cannot be guaranteed due to human factors. Large dedicated machines have advantages such as good accuracy, repeatability and high machining quality, but they are not flexible and require large installation space and a significant investment. In view of the above situation, industrial robots, which possess flexibility and low cost, have been adopted as effective platforms to perform drilling tasks, and some robotic drilling systems also have been developed and successfully used in the aerospace industry [1–4].

However, due to their relatively low stiffness, industrial robots have always suffered from static and dynamical deformation induced by cutting forces during the machining processes. The excessive static deformation may violate the positioning accuracy of the robot, and the dynamical deformation may lead to poor machining quality and inferior production efficiency [5,6]. Therefore, it is of great importance to increase the robot stiffness in machining applications. In fact, the robot stiffness is one of the major subjects of research in robotics and great attention has been given to this area. For a given standard robot, many research studies have discussed the following aspects: (1) stiffness modeling for serial and parallel manipulators [7–9]; (2) identification of stiffness parameters [10–12]; and (3) analysis of stiffness characteristics [11,13]. Yet the issue of how to increase the robot's stiffness is still to be studied.

The robot stiffness depends on the following factors: (1) geometric and material properties of the links; (2) actuators and other transmission elements; and (3) robot postures. In general, for a given standard robot, the first two factors seldom vary while its posture varies continuously when performing tasks, and hence its stiffness is mainly affected by the posture. Furthermore, a great number of machining operations such as drilling or milling only require five degrees of freedom (DOFs), where three DOFs are used to locate the tool center point (TCP) and another two DOFs are used to orient the tool axis. When a six-axis industrial robot is used to perform these machining operations, there is one redundant DOF [4,14–16]. Notice that the tool axis does not coincide in general with the axis of the last joint of the wrist, resulting that an infinite number of robot postures are available for a given position in the operational space. Therefore, it can be regarded as a feasible scheme to increase the robot stiffness by optimizing the robot posture. However, until now, there is not a proper performance index to measure how stiff a robot is at a certain posture. Angeles [13], a senior expert in robotics, suggests that the norm of

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the stiffness matrix would be a plausible candidate. Yet the stiffness matrix has entries with disparate physical units, resulting in the fact that its norm makes no physical sense. In this paper, the compliance matrix, which is the inverse of the stiffness matrix, is divided into blocks, and then the translational compliance submatrix (TCSM) which expresses the relationship between the translational displacement of the robot end effector (EE) and the force applied on it is obtained. With an in-depth study of the TCSM, a performance index in terms of the determinant of the matrix is proposed in order to evaluate the stiffness of a robot with a certain posture. Besides, based on the performance index, a posture optimization method is presented to increase the stiffness of the robot in machining applications.

The paper is structured as follows. In Section 2, the concept of the TCSM is deduced to express the relationship between the translational displacement of the robot EE and the force applied on it. Based on the TCSM, in Section 3, the stiffness characteristics of the robot in a certain direction is studied first, and then a performance index to evaluate the stiffness of the robot with a certain posture is proposed, followed by the analysis of the frame invariance of the index. By maximizing the stiffness performance index, a posture optimization model is established and solved by a novel solution method in Section 4. In Section 5, experiments to verify the stiffness performance index and the application of the posture optimization method in the robotic drilling system are described. Finally, the paper is concluded in Section 6.

2. Stiffness model of the robot

Intensive research has been done in robot stiffness modeling. Pashkevich et al. [9] summarized different types of models and their corresponding Cartesian stiffness matrices. Among them, the conventional model $\boldsymbol{K} = \boldsymbol{J}^{-T}\boldsymbol{K}_{\theta}\boldsymbol{J}^{-1}$ derived by Salisbury [7] and the enhanced model $\boldsymbol{K} = \boldsymbol{J}^{-T}(\boldsymbol{K}_{\theta} - \boldsymbol{K}_{C})J^{-1}$ derived by Chen and Kao [8] are most commonly used. However, both models involve calculating the inverse of the Jacobian matrix, which will introduce a calculation error, especially when the robot is close to singularity (the determinant of Jacobian matrix is close to zero). To avoid this problem, we adopt the compliance matrix derived by Abele et al. [11]. Assume that the links of the robot are infinitely stiff, then the dominant source of the compliance comes from the actuators and transmission elements, and it can be represented by a linear torsional spring for each joint, we can thereby obtain the relationship:

$$\Delta\boldsymbol{X} = \boldsymbol{C}\boldsymbol{F} \tag{1}$$

with

$$\boldsymbol{C} = \boldsymbol{J}\boldsymbol{K}_{\theta}^{-1}\boldsymbol{J}^{T} \tag{2}$$

where $\Delta\boldsymbol{X}$ is the generalized displacement of the EE, including the translational and rotational displacements;

$\boldsymbol{F}$ is the generalized force applied on the EE, including the force and torque;

$\boldsymbol{C}$ is the compliance matrix, inverse of the stiffness matrix;

$\boldsymbol{J}$ is the Jacobian matrix of the robot and can be derived from the robot's kinematic model using the vector product method proposed by Whitney [17]. In general, the robot kinematics are described by the standard Denavit–Hartenberg model [18]. For the KUKA KR360-2 robot considered in this paper, the Denavit–Hartenberg parameters are given in Table 1.

$\boldsymbol{K}_{\theta}$ is the joint stiffness matrix which is defined as:

Table 1
Denavit–Hartenberg parameters of the KUKA KR360-2 robot.

Joint	1	2	3	4	5	6
L (mm)	500	1300	55	0	0	0
D (mm)	1045	0	1025	0	290	0
α (deg)	0	90	0	−90	90	-90

$$\boldsymbol{K}_{\theta} = \begin{bmatrix} k_1 & 0 & \dots & 0 \\ 0 & k_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & k_6 \end{bmatrix} \tag{3}$$

where k_i, $i = 1, \dots, 6$ is the ith joint stiffness which can be identified by experiments using the method described in literature [12]. For the KUKA KR360-2 robot, the joint stiffness matrix $\boldsymbol{K}_{\theta}$ is identified as: $\boldsymbol{K}_{\theta} = \mathrm{diag}$

$$\cdot\begin{bmatrix} 1.199\mathrm{E}10 & 5.0\mathrm{E}9 & 4.367\mathrm{E}9 & 2.217\mathrm{E}9 & 2.301\mathrm{E}9 & 2.328\mathrm{E}9 \end{bmatrix}$$
Nmm/rad.

The model above represents the relationship between the generalized displacement of the robot EE and the generalized force applied on it. Yet the compliance matrix $\boldsymbol{C}$ has entries with disparate physical units. This results in difficulties in studying the compliance, and also the stiffness characteristics of the robot. Considering the fact that in machining operations, the rotational displacement of the tool can be negligible with respect to its translational displacement and the cutting torque applied on the tool can be neglected [16], we will mainly study the relationship between the translational displacement of the robot EE and the force applied on it in this paper. Assume that the rotational displacement of the EE and the torque applied on it are zero, the Eq. (1) becomes:

$$\begin{bmatrix} \Delta\boldsymbol{X}_t \\ 0 \end{bmatrix} = C\begin{bmatrix} \boldsymbol{F}_f \\ 0 \end{bmatrix} \tag{4}$$

where $\boldsymbol{F}_f = \begin{bmatrix} F_x & F_y & F_z \end{bmatrix}^T$ is the force applied on the EE, $\Delta\boldsymbol{X}_t = [\Delta x \quad \Delta y \quad \Delta z]^T$ is the translational displacement of the EE.

And then divide the compliance matrix $\boldsymbol{C}$ in four blocks,

$$\boldsymbol{C} = \begin{bmatrix} \boldsymbol{C}_{tt} & \boldsymbol{C}_{tr} \\ \boldsymbol{C}_{tr}^{T} & \boldsymbol{C}_{rr} \end{bmatrix} \tag{5}$$

where $\boldsymbol{C}_{tt}$ is the translational compliance submatrix (mm/N), $\boldsymbol{C}_{rr}$ is the rotational compliance submatrix (rad/Nmm), and $\boldsymbol{C}_{tr}$ is the coupling compliance submatrix (rad/N).

Substitute Eq. (5) into Eq. (4) and expand it, which becomes:

$$\Delta\boldsymbol{X}_t = \boldsymbol{C}_{tt}\boldsymbol{F}_f \tag{6}$$

It is apparent that the translational compliance submatrix transforms the force applied on the robot EE into its small translational displacement in three-dimensional space. In matrix $\boldsymbol{C}_{tt}$, all the elements have the same physical unit avoiding the problem of incompatible units which exits in matrix $\boldsymbol{C}$. It should be noted that the translational compliance submatrix is not the inverse of the translational stiffness submatrix as shown in [13].

3. Performance index of the robot stiffness

3.1. Stiffness characteristics of the robot in a certain direction

The stiffness of the robot is posture dependent. Furthermore, for a robot with a given posture, the stiffness in different directions varies widely. To study the overall stiffness of the robot, the