Robotics and Computer Integrated Manufacturing 55 (2019) 19–28

Contents lists available at ScienceDirect

Robotics and Computer Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Stiffness-based pose optimization of an industrial robot for five-axis milling

Gang Xiong, Ye Ding, LiMin Zhu*

State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

ARTICLE INFO

Keywords:
Robot machining
Five-axis milling
Stiffness performance index
Redundancy elimination
Pose optimization
Kinematical constraints

ABSTRACT

Industrial robot provides an optimistic alternative of traditional CNC machine tool due to its advantages of large workspace, low cost and great flexibility. However, the low posture-dependent stiffness deteriorates the machining accuracy in robotic milling tasks. To increase the stiffness, this paper introduces a pose optimization method for the milling robot when converting a five-axis CNC tool path to a commercial six-axis industrial robot trajectory, taking advantage of a redundant degree of freedom. First, considering the displacements of at least three points on the end effector of the robot, a new frame-invariant performance index is proposed to evaluate the stiffness of the robot at a certain posture. Then, by maximizing this index, a one-dimensional posture optimization problem is formulated in consideration of the constraints of joint limits, singularity avoidance and trajectory smoothness. The problem is solved by a simple discretization search algorithm. Finally, the performance index and the robot trajectory optimization algorithm are validated by simulations and experiments on an industrial robot, showing that the machining accuracy can be efficiently improved by the proposed method.

1. Introduction

Industrial robot (IR) is recognized as an effective alternative of traditional CNC machine tool for the large and complex shaped product manufacturing in aerospace industry due to its advantages of large workspace, low cost and great flexibility [1–3]. There is a trend to extend the IR application areas from traditional repetitive tasks to high accuracy milling applications [4,5]. However, despite intensive research, IRs are rarely used in milling applications in industry. One of the main obstacles for high-accuracy robot milling is the low stiffness of the robot [6], resulting in deformations and vibrations induced by cutting forces during the machining processes [7]. This will lead to poor machining accuracy and deficient surface quality of the machined part. It is of great significance to increase the robot stiffness in machining applications.

In most CAM softwares for robot milling application, the robot cutting trajectory is usually converted from the cutter location (CL) data generated by a five-axis milling module in a commercial CAD/CAM software package [8]. A standard commercial IR usually has 6 degrees of freedom (DOFs). Nevertheless, a typical milling task only requires five DOFs, three of which are used to locate the tool center point (TCP) and the rest two are used to determine the tool axis direction. So, using a six-axis IR to perform five-axis milling tasks will result in one redundant DOF, which is the rotation about the cutter axis. The redundant DOF exists because the tool axis and the last joint axis of the wrist are always mounted non-collinearly to improve the dexterity and manipulability of the robot [9]. The redundancy causes troubles in solving inverse kinematics when performing general five-axis milling tasks, whereas it also provides an opportunity to optimize the robot posture given a specified CL. Therefore, the major concern in robot milling trajectory generation becomes redundancy elimination, i.e., pose optimization of the robot according to a certain performance index.

Until recently, many performance indexes have been proposed for the milling robot [9–15], such as the dexterity index, the joint limit index [9–11], the robot transmission ratio index [14] and so on. These indexes mainly concentrate in improving the kinematic or dynamic performance of the robot while neglect the insufficient stiffness. Generally, the stiffness of an IR mainly depends on the torsional stiffness of the gearbox and the drive shaft of each joint, the links are assumed to be rigid, and the Cartesian stiffness is posture dependent [16]. Therefore, it is possible to optimize the robot posture based on a stiffness-based performance index. Dumas et al. [17,18] suggest that the sum of the deformations along the cutting trajectory should be minimized when eliminating the redundant DOFs of the robot in milling. The machining quality is improved via this method as the deformations responsible for machining errors are suppressed. However, this method relies on the prediction of the process forces, which is a complex task. Bu et al. [19,20] and Lin et al. [21] take the feed direction stiffness as the optimization index after a detailed analysis of the robot stiffness

* Corresponding author.
E-mail addresses: xionggang@sjtu.edu.cn (G. Xiong), y.ding@sjtu.edu.cn (Y. Ding), zhulm@sjtu.edu.cn (L. Zhu).

https://doi.org/10.1016/j.rcim.2018.07.001
Received 19 December 2017; Received in revised form 8 May 2018; Accepted 3 July 2018

characteristic. Nevertheless, this criterion is more suitable for robot drilling applications. Generally, it's hard to evaluate the overall stiffness of a robot at a certain posture due to the different units in the stiffness matrix, which makes the eigenvalue-based performance criteria have no physical meanings. To deal with this, Taghvaeipour et al. [22] and Wu et al. [23,24] extract the rotational and translational stiffness indices respectively by nondimensionalizing the stiffness matrix. The effectiveness of this method is not verified in machining applications. On the other hand, Guo et al. [25] propose a performance index in terms of the determinant of the translational compliance sub-matrix (TCSM). Though this index is verified to be effective in drilling applications, it is incomplete yet as it neglects the rotational deformations of the end effector (EE). Another problem in optimizing the robot posture is the algorithm to be used. It is worth mentioning that the problem discussed here is a one-dimensional optimization problem [9,11]. Though many complicated algorithms, such as the genetic algorithm [13,17], the gradient based algorithm [12] and so on, have been proposed to solve the optimal problem with different optimization objectives, the classical discretization search method is a good choice.

In this paper, a new stiffness-based performance index is proposed to optimize the IR posture when generating a six-axis IR trajectory from a five-axis CNC tool path. This index takes the complete compliance matrix into consideration and measures the overall stiffness of the robot at a certain posture. Maximizing this index will lead to an optimal robot configuration with less deformation of the EE. On the other hand, a discretization search algorithm is proposed to solve the optimization problem considering the constraints of joint limits, singularity avoidance and the smoothness of the robot trajectory. Via enhancing the robot stiffness, the proposed trajectory generation method has an advantage of improving the machining accuracy. This will pave the way to the vast applications of robot milling in scenes of rough machining and semi-finishing. With regard to tasks with strict accuracy requirements, an off-line or online error compensation process remains necessary yet, while that is out of the scope of this paper.

The remainder of this paper is organized as follows. In Section 2, the mathematical formula of the redundancy is presented. In Section 3, a new stiffness-based performance index is proposed, and its advantages are analyzed. In Section 4, the mathematical model and algorithm for optimizing the six-axis IR posture for five-axis milling applications is developed. In Section 5, simulations and experiments are conducted to confirm the validity of the proposed approach. Section 6 concludes the paper.

2. Redundancy in robot milling

The most important task of trajectory generation for a milling robot is to determine the set of revolute joint variables θ_i $(i = 1, \cdots, 6)$ from the CL data $\boldsymbol{CL}(x, y, z, i, j, k)$, where (x, y, z) is the coordinate of the TCP, and (i, j, k) is a unit vector representing the tool axis direction. Practically, the CL data is generated in a commercial CAD/CAM software such as NX, and the positions and orientations are all described in the workpiece coordinate frame. Once the CL data $\boldsymbol{CL}(x, y, z, i, j, k)$ is given, the posture of the EE of the robot with respect to the workpiece coordinate frame can be determined, and it can be represented by a six-dimensional vector $(x, y, z, \alpha, \beta, \gamma)$, where α, β and γ are the $z-y-z$ type Euler angles. After obtaining the posture of the EE, the robot joint angles can be calculated via inverse kinematics.

Let a frame $O_tX_tY_tZ_t$ attach to the cutter with its origin at the TCP and its z axis along the tool axis, as shown in Fig. 1. The frame is described by a six-dimensional vector $(x, y, z, \alpha, \beta, \gamma)$ with respect to the workpiece frame, i.e., $O_wX_wY_wZ_w$, the corresponding homogeneous transformation matrix ${}^{w}\boldsymbol{T}_t$ is

$$ {}^{w}\boldsymbol{T}_t = rot(z, \alpha)rot(y, \beta)rot(z, \gamma)trans(x, y, z) \tag{1} $$

where *rot* and *trans* denote the rotation and translation transformations, respectively. To perform a milling task, the CL data $\boldsymbol{CL}(x, y, z, i, j, k)$ and

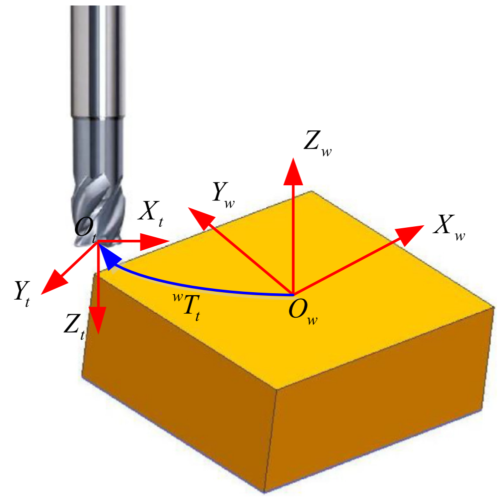

Fig. 1. The transformation from the workpiece frame to the tool frame.

the transformation matrix ${}^{w}\boldsymbol{T}_t$ have to satisfy

$$ \begin{bmatrix} i & x \\ j & y \\ k & z \\ 0 & 1 \end{bmatrix} = {}^{w}\boldsymbol{T}_t \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -1 & 0 \\ 0 & 1 \end{bmatrix} \tag{2} $$

It can be deduced from Eqs. (1) and (2) that

$$ [i \quad j \quad k]^T = [-\cos\alpha\sin\beta \quad -\sin\beta\sin\alpha \quad -\cos\beta]^T \tag{3} $$

Eq. (3) shows that given a CL point $\boldsymbol{CL}(x, y, z, i, j, k)$, the former five components of the six-dimensional vector $(x, y, z, \alpha, \beta, \gamma)$ can be determined, while the third Euler angle γ is arbitrary. Therefore, there exist infinite robot configurations that can produce the specified CL point. The third Euler angle γ may be treated as the redundant DOF, and it should be uniquely determined via optimization. Once an optimal third Euler angle γ_{opt} is obtained, the optimal robot configuration $\boldsymbol{\theta}(\boldsymbol{CL}, \gamma_{opt}) = [\theta_1, \theta_2, \cdots, \theta_6]^T$, can be uniquely determined via the closed-form inverse kinematic solutions [26].

3. Stiffness-based performance index

3.1. Stiffness model

In general, it's very complex to model the stiffness characteristic of an IR due to the existence of backlash, clearance and other nonlinear factors [27–29]. However, it is well acknowledged that the robot stiffness mainly depends on the torsional stiffness of the gearbox and the drive shaft of each joint [30]. Therefore, in practice, each joint of the robot is modeled as a linear torsion spring. A constant 6×6 diagonal matrix $\boldsymbol{K}_\theta$ with each diagonal term characterizing the stiffness of a joint is used to represent the robot joint space stiffness [31,32], i.e.,

$$ \boldsymbol{K}_\theta = diag([K_{\theta_1}, K_{\theta_2}, K_{\theta_3}, K_{\theta_4}, K_{\theta_5}, K_{\theta_6}]) \tag{4} $$

The Cartesian stiffness of the EE is

$$ \boldsymbol{K}_x = \boldsymbol{J}^{-T}(\boldsymbol{K}_\theta - \boldsymbol{K}_c)\boldsymbol{J}^{-1} \tag{5} $$

where $\boldsymbol{J}$ is the Jacobian matrix, and $\boldsymbol{K}_c = \left[\frac{\partial \boldsymbol{J}^T}{\partial \theta_1}\boldsymbol{F}, \frac{\partial \boldsymbol{J}^T}{\partial \theta_2}\boldsymbol{F}, \frac{\partial \boldsymbol{J}^T}{\partial \theta_3}\boldsymbol{F}, \frac{\partial \boldsymbol{J}^T}{\partial \theta_4}\boldsymbol{F}, \frac{\partial \boldsymbol{J}^T}{\partial \theta_5}\boldsymbol{F}, \frac{\partial \boldsymbol{J}^T}{\partial \theta_6}\boldsymbol{F}\right]$ with $\boldsymbol{F}$ denoting the external six-dimensional wrench vector applied on the robot EE. Since the effect of $\boldsymbol{K}_c$ on the total robot deformation is very small under the normal robot loads, this term can be omitted [16]. Then, Eq. (5) becomes

$$ \boldsymbol{K}_x = \boldsymbol{J}^{-T}\boldsymbol{K}_\theta\boldsymbol{J}^{-1} \tag{6} $$

The six-dimensional differential motion of the EE caused by the deformation of the IR under the external wrench $\boldsymbol{F}$ has the expression