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Posture optimization methodology of 6R industrial robots for machining using performance evaluation indexes

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ABSTRACT

For industrial robots, the relatively low posture-dependent stiffness deteriorates the absolute accuracy in the robotic machining process. Thus, it is reasonable to consider performing machining in the regions of the robot workspace where the kinematic, static and even dynamic performances are highest, thereby reducing machining errors and exhausting the advantages of the robot. Simultaneously, an optimum initial placement of the workpiece with respect to the robot can be obtained by optimizing the above performances of the robot. In this paper, a robot posture optimization methodology based on robotic performance indexes is presented. First, a deformation evaluation index is proposed to directly illustrate the deformation of the six-revolute (6R) industrial robot (IR) end-effector (EE) when a force is applied on it. Then, the kinematic performance map drawn according to the kinematic performance index is utilized to refine the regions of the robot workspace. Furthermore, main body stiffness index is proposed here to simplify the performance index of the robot stiffness, and its map is used to determine the position of the EE. Finally, the deformation map obtained according to the proposed deformation evaluation index is used to determine the orientation of the EE. Following these steps, the posture of the 6R robot with the best performance can be obtained, and the initial workpiece placement can be consequently determined. Experiments on a Comau Smart5 NJ 220-2.7 robot are conducted. The results demonstrate the feasibility and effectiveness of the present posture optimization methodology.

1. Introduction

Traditionally, the IRs were dedicated to repetitive tasks with relatively low accuracy, such as pick-and-place, welding and painting, while the CNC machine tools were usually applied in the high-accuracy machining where the external force is not negligible or constant. However, due to various advantages of the IRs such as flexibility, maneuverability, large workspace and relatively low cost, nowadays the IRs are becoming widely utilized in the machining operations including grinding, drilling and even milling. The European Union funded research program COMET [1–4], which lasted from 2010 to 2013, aimed to achieve accuracy level of less than 50 μm in milling applications. Another European collaborative project entitled "Hard Material Small-Batch Industrial Machining Robot (HEPHESTOS)" [5] started in 2012, whose main objective is to develop cost-efficient robotic machining technologies for hard materials with small-batch. However, IRs can reach accuracy within the range of about 0.3–0.5 mm [6] provided proper calibration procedures (e.g. tool calibration), which is only a factor of 60–100 less compared to CNC [7]. Thus, how to achieve high accuracy is the major concern in the robotic machining applications.

The main obstacle for high-accuracy robotic machining is the IRs' insufficient and posture-dependent stiffness, which significantly deteriorates the robotic absolute accuracy when tracking continuous tool paths with the varied cutting force applied on the EE. The stiffness for 6R IRs is usually less than 1 N/μm [8,9], while that for CNC machines is usually larger than 50 N/μm [10]. Furthermore, the kinematic performance should be also considered to avoid the IR moving in singularities during the machining process. Thus, it is reasonable to perform machining in the regions where the kinematic and stiffness performances are the best, which means the initial placement of the workpiece with respect to the robot should be optimized before machining.

Regarding the machining performance, there are already many kinds of evaluation indexes proposed, such as kinematic, stiffness and dynamic performance indexes. To evaluate the kinematic performance, Yoshikawa [11] introduced the concept of manipulability to check whether the robot is in singularities [12]. Angeles and Rojas [13] adopted the condition number of Jacobian matrix to measure the

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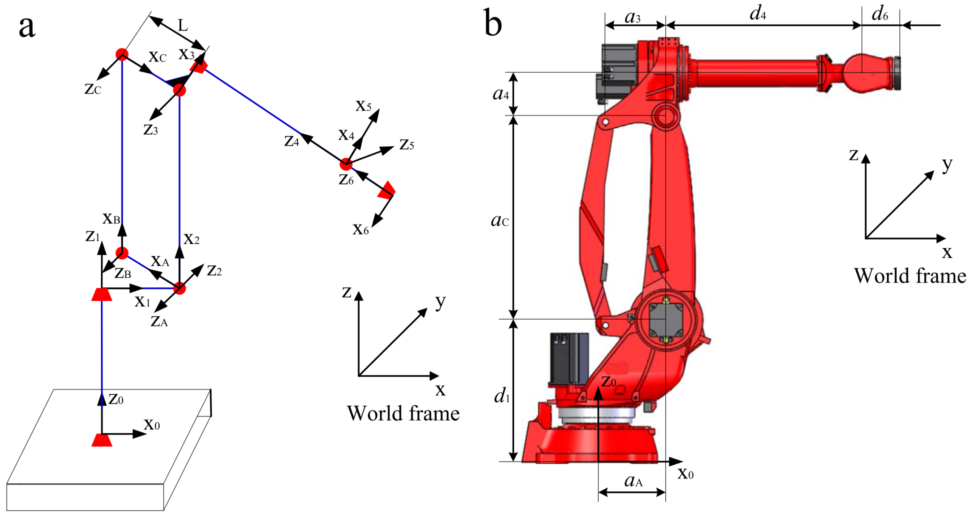

Fig. 1. DHm parameterization of the robot with kinematic parallelogram. (a) Kinematic modeling. (b) Kinematic parameters.

Table 1
DHm parameters of the robot with kinematic parallelogram.

Joint i	1	A	B	C	3	4	5	6
θ_i (rad)	θ_1	$\theta_3 - \pi/2$	$-\theta_2 - \theta_3 - \pi$	$\theta_2 + \theta_3$	$\pi/2$	θ_4	θ_5	$\theta_6 + \pi$
d_i (mm)	830	0	0	0	0	−1125.33	0	−230
a_i (mm)	0	400	350	1175	350	250	0	0
α_i (deg)	0	90	0	0	0	−90	−90	90

distance to singularities. Wu and Gosselin [14] obtained the singularity loci by using the expression of the determinant of the Jacobian matrix. For serial manipulators like IRs, to evaluate the stiffness performance, Salisbury [15] proposed a conventional stiffness model, and then Chen and Kao [16] improved such model. However, both models involve calculation of the inverse Jacobian matrix, which inevitably introduces evaluation errors, especially when the robot is close to singularities. To avoid undesirable calculation errors, Abele et al. [17] derived a compliance model based on Refs. [18,19], and then applied the compliance model calculation method and the direct measurement method to obtain the compliance of IRs, respectively. Then, Guo et al. [20] proposed a performance index to evaluate the robot compliance matrix [21]. By maximizing such index, a robot posture optimization model is further established. However, these indexes proposed in the above references are only posture-dependent, not task-dependent. It is well known that the “task-dependent” means machining performances depend on different machining operations. To solve this problem, Zargarbashi et al. [22] proposed a task-dependent dynamic performance index called robot transmission ratio, to quantify the effectiveness of the actuator force in producing a prescribed robot orientation. And Wu et al. [23] proposed a new industry-oriented performance measure for optimal measurement configuration. This approach aimed at finding the calibration configurations, which ensure the best robot positioning accuracy after geometric error compensation. For parallel robot, Imoto et al. [24] proposed an error index that can be used to determine the optimal measurement poses for calibration. And it depends on the kinematic parameters of the robot, calibration conditions and error evaluation conditions specified by the robotic task.

Regarding the robot machining posture and the initial workpiece placement optimization, Ref. [20] presented a posture optimization method aiming to find the optimum robot configuration with the best stiffness performance based on the performance index of the robot stiffness in a drilling system. Ref. [22] proposed a posture optimization method to produce a prescribed robot orientation based on robot transmission ratio index in a face-milling operation. However, the above methods focus on orientation selection for a specified machining position, so only local optimization results are obtained. To obtain the optimal machining posture, workpiece placement has to be optimized in the global robot workspace. Lueth [25] presented a new approach for planning robot workcells automatically in three dimensions. This new planning approach enhances the conventional layout planning process and reduces the necessity of user interaction. Zhang and Fang [26] put forward a practical methodology to minimize the cycle time for certain patterned robotic cell layouts in small part assembly by achieving the optimum deployment of the tasks, with an incensement in productivity up to 15%. However, the above two methods aim at improving the machining efficiency, not the machining performance. Caro et al. [27] introduced a methodology that aims to determine the best placement of the workpiece. This proposed methodology can be conducted under knowing the cutting forces exerted on the tool and the elastostatic model of the robot. And it can be used to find the optimum placement of any workpiece within the Cartesian workspace of any 6R IRs. However, in some operations, optimization by their approaches in the whole robot workspace may cost too much time and may not obtain the ideal result.

To optimize the initial placement of the workpiece with respect to the robot, where the kinematic and stiffness performances can be the best during the machining process, this paper proposes a global posture optimization methodology. The methodology is based on the kinematic, stiffness and deformation maps drawn by using the existing and proposed performance evaluation indexes, and it consists of three steps. First, kinematic performance index is used to plot kinematic performance map which can identify the kinematic performance of the whole robot workspace. The area which is far from singularities (make the robot workspace not in singularities or close to singularities) in the map is refined. Second, main body stiffness index, which is proposed as the simplified performance index of the robot stiffness, is adopted to draw stiffness map in the refined workspace, and resultantly optimize Joint 2 and Joint 3 (J2 and J3 for short, the same below). Third,