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Postprocessor for Verification of Robot Movements with Additional Axis after Toolpath Optimization

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Abstract

This paper discusses a postprocessor for milling robots connected to additional linear machine axes where toolpath is optimized with respect to variable properties of the robot in its workspace. A toolpath optimization method is proposed based on an experimentally verified robot stiffness model. After postprocessor distribution of the movements between the robot and the linear axes, the collision states during machining cannot be verified in common CAM. Therefore, a solution enabling simulation of movements after optimization is proposed. The tool center point coordinates are used to control the robot and additional machine axes, while the joint coordinates calculated by inverse kinematic transformation are used to verify the movements.

Keywords: Robot; Tool path; Simulation; Milling; Computer aided manufacturing; Postprocessor; Robot stiffness

1. Introduction

Recently, industrial robots have been more commonly used for tasks other than just pick and place or welding applications, such as milling operations or hybrid manufacturing, as described by Baier et al. [1]. Stary et al. [2] present a way of using robots for applications that had been formerly implemented through chemical processes like glass frosting. All of these tasks call for new ways of planning toolpaths and simulating the NC program (control program) as well as optimizing toolpaths to achieve the best possible results.

A major challenge in robotic machining applications is low static and dynamic stiffness of the robot. This issue is approached by several research studies in different ways. For example Xiong et al. [3] presented a way of using redundancy around the tool axis during five axis milling. The authors propose a stiffness-based performance index and find the stiffest configuration by using a discretization algorithm. Guo et al. [4] suggested a similar approach for drilling and boring operations implemented by a robot. However, these methods may reduce the working area of the robot since in some cases the stiffest configuration cannot be attained. Baier et al. [1] developed an online optimization algorithm that can compensate forces during robotic milling operations and added an offline module to predict forces during strong force changes to allow for compensation in the desired cycle time.

This paper presumes an industrial robot extended by additional linear axes that carry the robot. These axes add further degrees of freedom and offer the possibility of optimizing various parameters affecting machining operations. Basically, position of the robot base in the workspace relative to the workpiece is optimized to achieve a toolpath with the

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best possible properties. This could lead to e.g. higher machining speed and therefore higher productivity or, as mentioned before, enhanced stiffness of the structure and therefore better surface quality and machining precision. Diaz et al. [5], for example, studied an approach suitable for robotic welding operations using additional axes. A tilting table is added to the robot cell. The optimal welding orientation is obtained by minimalizing robot joint movements and avoiding gravity effects using a positioner.

Other studies focusing on robotic behaviors during machining namely vibration instabilities, include works of Tunc and Secer [6], Mousavi et al. [7] and Huynh et al. [8], where a dynamic model of a robot is created that can be used to predict the posture-dependent dynamics of the robot. This model may then be integrated into motion planning to avoid excessive vibrations and chatter.

The task is not only to create an optimization algorithm but also to find an effective way of implementing it into motion planning or into NC program preparation.

This paper focuses on ways of implementing optimization algorithms into a postprocessor, which is a software that generates the final NC program for a robotic cell based on motion planning done in CAM software. A robot substitute stiffness model for a Stäubli TX200 robot based on measured data is also presented and a stiffness criterion is proposed. The criterion may be used to find the optimal position of the robot base carried by the additional linear axes with respect to maximal robot stiffness while machining.

Nomenclature

t	Vector representing end effector position and orientation in the base coordinate system
J	Jacobian matrix of a robot
θ	Robot joint coordinates [°]
K_t	Cartesian stiffness matrix in the base coordinate system
K_θ	Diagonal matrix including the stiffness of each joint's gearbox
K_c	Complementary stiffness matrix
K_{sf}	Stiffness criterion [-]
α	Weight of maximum stiffness value [mm^2/N^2]
β	Weight of mean stiffness value [mm^4/N^4]
k_i	Robot directional stiffness at a given toolpath point [N/mm]

2. Optimization algorithm and its implementation into the postprocessor

2.1. Substitute stiffness model

In papers by Xiong et al. [3], Guo et al. [4] and Celikag et al. [9] a mathematical stiffness model of a robot is shown. This model takes into account only the torsional stiffness of the gearboxes in each joint, other stiffnesses, i.e. directional and torsional are omitted. If K_θ is a diagonal matrix containing the stiffness of each joint's gearbox and J is a Jacobian matrix of the selected robot defined as (1) where Δθ is the increment in joint coordinates and Δt is the increment in the Cartesian coordinates of the robot's end effector then the model is expressed as (2) where K_t is the Cartesian stiffness in the base coordinate system and K_c is the complementary stiffness matrix.

$$\Delta t = J \cdot \Delta\theta \quad (1)$$

$$K_t = J^{-T}(K_\theta - K_c)J^{-1} \quad (2)$$

If we take into consideration only the unloaded manipulator for the sake of finding only the stiffest configuration regardless of external load the model becomes (3) and it can be used in this form in optimization algorithms.

$$K_t = J^{-T}K_\theta J^{-1} \quad (3)$$

This paper, however, proposes a more complex stiffness model based on experimentally measured data. This model includes the directional and torsional stiffnesses that form the diagonal stiffness matrix of each joint. Therefore, six stiffnesses in each joint are considered as opposed to the model represented by (3) where only one torsional stiffness in each joint is taken into account. In addition, the stiffness of each joint depends on its rotation.

Data were measured for a Stäubli TX200 robot with a Leica AT901 Laser Tracker. Adjoining robot arms were fitted with retroreflectors for each joint and deflection was measured while force was applied to the robot flange in flange coordinate system in the X, Y and Z directions. The flange was equipped with force sensor evaluating the force vector. Applied force was ascending from 0N to 600N and then descending with the step of 150N. Fig. 1 shows the measurement of θ5 deflection. The force is applied in the Z direction of the flange in this case.

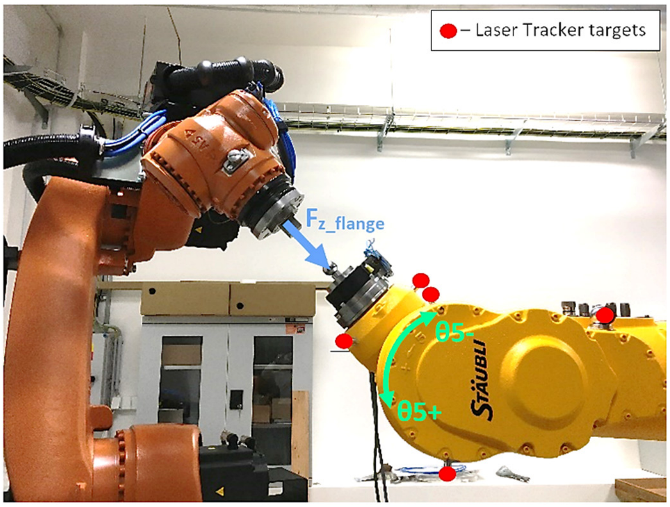

Fig. 1. Measurement of θ5 deflection

Based on the measured mutual displacement of the robot arms that were considered absolutely stiff and known forces operating in the joint coordinate system (calculated with the robot kinematic model from known forces applied to the robot's flange) directional and torsional stiffnesses were determined for each joint based on its rotation. From the measured data it is clear that some of the directional deformations and twists in directions other than those in gearbox axes are not negligible. For example, Fig.2 shows that the maximum twist in the X axis of joint θ2 is 0.01° (represented by the valleys in green areas in Fig.2 were force is applied in Y direction of flange coordinate system) whereas in Z axis (gearbox axis) is the twist 0.017° with the same bending loading; in conclusion, the twist in the X axis contributes to the total robot deformation similarly to the twist in the Z axis and therefore the torsional stiffness in the X axis of joint θ2 is not negligible.

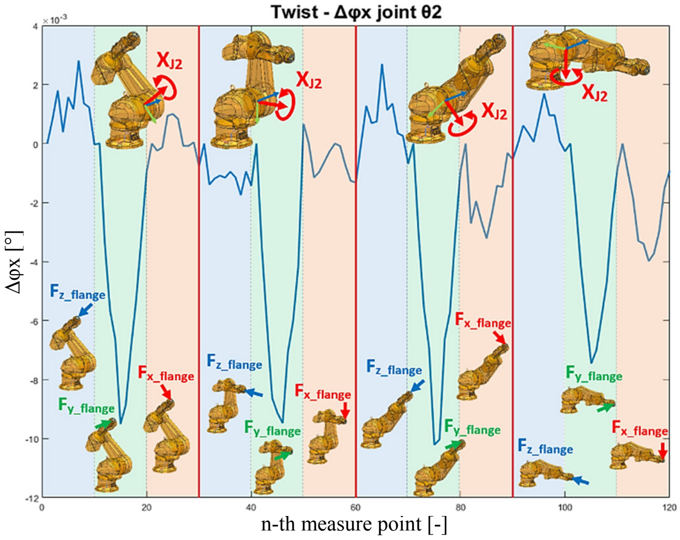

Fig. 2. Twist around X axis of joint θ2

The stiffness model based on the measured data was created in Matlab software. This model can be used as a basis for the optimization algorithm used during postprocessing. Fig. 3 shows an example of a stiffness map generated by the model. The stiffness represented by the colorbar is the mean value of directional stiffnesses in the flange coordinate system calculated from the absolute displacement values in the X, Y and Z flange axes directions caused by a cluster of unit forces. In this case the origin of the map was located 1344 mm in the X direction and 550 mm in the Z direction from the base coordinate system of the robot. The flange coordinate system was not rotated in any axis at all points of the map.

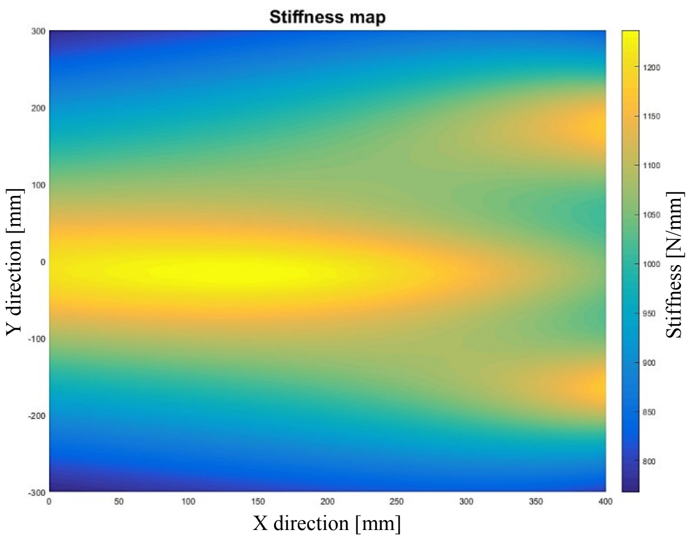

Fig. 3. Stäubli TX200 robot stiffness map (mean value of directional stiffnesses) in the selected workspace

2.2. Implementation of inverse kinematics and optimization algorithms into the postprocessor

In order to find the optimal orientation of the robot based on the selected optimization criterion, the robot joint values at all points of the toolpath must be known. This requires converting the point coordinates of the toolpath defined in Cartesian space to joint space coordinates. This is done using inverse kinematics. The robot stiffness in a given configuration may be calculated using the described substitute stiffness model as soon as the joint values are obtained.

Since the inverse kinematic calculation needs to be done at each point of the toolpath it has to be implemented in the postprocessor. This is a problem since postprocessors commonly used for robots and CNC machines usually do not support inverse kinematic calculations and are programmed in languages (e.g. the TCL programming language) that do not have the desired computing abilities. One possibility is to create an external application containing the inverse kinematic calculation that will be called up during postprocessing. Similarly an optimization algorithm can by implemented that will obtain data both from the postprocessor and the inverse kinematic calculation. This makes it possible to create a complex application whose outputs consist of programs that are directly suitable for the machine tool´s control system and also for virtual simulation of the machining task.

An emulator of machine control system is needed for simulation of the generated NC program. Current emulators used for robot machining are not commonly used in CAM software. Simulations are based on internal CL data and not on the final generated NC program. However, the emulator containing the inverse kinematic calculation is not needed if a version of the NC program containing joint space coordinates can be obtained. As mentioned earlier, with these calculations implemented into a postprocessor as external applications, such output can be generated. If, then, a simplified emulator is created that runs a NC program in joint coordinates and it is possible to simulate machining before running the program in the real robotic cell.

2.3. Design of optimization algorithm based on stiffness criterion

To take advantage of the robot stiffness calculation in a given configuration, it is possible to create an optimization algorithm. It will find the best position for robotic machining that can be reached through the additional linear axes. A stiffness criterion was proposed by the authors for evaluation of all potential configurations attainable by the linear axes. This criterion takes into consideration directional stiffness in the cutting force direction at all points of the toolpath in a given configuration. By introducing a suitable mathematical formulation of the criterion, the desired aspects of each configuration are rated. The integral criterion (4) (where k_i is robot directional stiffness at each point of the toolpath and α and β are weights) takes into consideration the mean value of stiffness and also sum of all stiffnesses squared, therefore evaluating maximum directional stiffness achieved during machining.

$$K_{sf} = \alpha \cdot \sum_{i=1}^{n} k_i^2 + \beta \cdot \left(\frac{\sum_{i=1}^{n} k_i}{n}\right)^4 \quad (4)$$

When several different positions of the robot relative to the workpiece are evaluated the one with the highest criterion value that the robot can by positioned to (by the linear axes in the selected workspace) may be chosen as the best for the given operation. However, only the criterion is proposed in this paper. The development of the algorithm distributing the movements is the aim for future work.

3. Experimental validation of the substitute stiffness model

To validate created stiffness model, deflection of the robot flange was measured by laser tracker in several configurations while known force was applied to it. Tab 1. shows compared directional stiffnesses from the measurement and from the model. The maximum relative error of the model within these configurations is 13.73% which is satisfactory because the model is not used for predicting precise deflection of the robot flange but only for comparing stiffnesses of different robot poses.

Tab. 1. Stiffness model validation

Config.	Force and direction [N]	Dir. stiffness – measured [N/mm]	Dir. stiffness – from the model [N/mm]	Rel. error [%]
1.	596.9 – Z	1187.95	1148.79	3.3
2.	601.8 – XY	506.19	436.68	13.73
3.	610.0 – Z	1135.99	1170.07	3

4. Experimental implementation of algorithms into the postprocessor

A postprocessor with additional user functions was developed with the Add on Post Configurator tool of Siemens NX CAM. The following functions were tested: inverse kinematic calculation and a basis for implementing optimization algorithms. The NX Open module, which enables development of user applications using common programming languages, was used to create DLL libraries. These libraries contain user functions and are created in Matlab as a C++ source code. This object was then implemented into the source code in Visual Studio and a DLL library was built. The postprocessor can call up the DLL at any time during the NC program generation and the functions can be used to optimize the toolpath and to generate output for simulation. The work scheme of the enhanced postprocessor is shown in Fig. 5. This technique of implementation of functions as external libraries allows use of multiple functions and algorithms with the strong computing power of programming languages like C++.

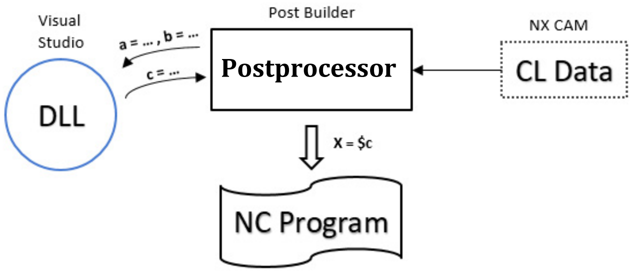

Fig. 5. Work scheme of the enhanced postprocessor

5. Conclusion

A postprocessor extended by external functions was presented in this paper. The postprocessor is designed for a milling robot carried by the additional linear axes. A substitute stiffness model of a Stäubli TX200 robot based on experimentally measured data was also presented. The substitute stiffness model is to be used as a base for tool path optimization algorithms which can be implemented into the postprocessor. Veracity of the model was experimentally validated. Furthermore the postprocessor can output a NC program in robot joint coordinates that can be used to simulate machining. This can be used, for example, to avoid collision states. Future work will focus on creating an optimization algorithm that will use the proposed stiffness criterion and will find optimal positions for machining using additional linear axes. Optimized NC programs will then be evaluated by test machining.

Acknowledgements

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