Kinematic Based Selection of the Workpiece Location in Robotic Milling

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Abstract

The use of industrial robots in milling applications exhibits several issues such as low accuracy, low structural rigidity and kinematic singularities etc. The inverse kinematic solution of the robot i.e. positions and motion of the axes, strictly depends on the workpiece location with respect to the robot base. Therefore, workpiece placement is crucial for improved robotic milling applications. In this paper, the effect of workpiece location in robotic milling is investigated considering the robot kinematics. The investigation criterion is selected as the movement of the robot axes. It is aimed to minimize the total movement of either all axes or selected the axis responsible of the most accuracy errors. Kinematic simulations are performed on a representative milling tool path and results are discussed.

Keywords: Workspace optimization, Robotic milling, Manufacturing productivity

1 Introduction

Articulated robots were mostly used in pick and place, assembly and welding processes. However, use of industrial robots for milling tasks is an emerging approach for the last decade, especially for large scale parts and/or parts requiring relatively less accuracy such as composites. Yet, 80% of the robots in industry are assigned to material handling type of tasks and as well as welding. Less than 5% of them are used in material removal operations, where most of such processes are deburring type requiring compliant tools [1]. In this regard, use of robots for milling tasks is relatively limited. Industrial robots demonstrate several advantages such as increased reconfigurability, foot print to and work envelope ratio, kinematic flexibility, low capital investment and material handling costs compared to computer numerical controlled (CNC) machines.

Workpiece placement with respect to the base of the machining unit, i.e. machine tool or robot, is an important decision in multi axis machining processes [2-5]. In multi axis, the orientation and positioning of the workpiece may be chosen randomly by the NC programmer or manufacturing engineer. However, it may lead to excessive cycle times due to redundant rotations and accuracy issues. It is known that the cycle time on the machine is usually different than the one on CAM screen. The ratio of actual to theoretical time depends on how the part is located, especially in 5-axis milling. Pessoles et al. [2] proposed an algorithm for optimization of workpiece location on tilt rotary table type 5-axis machine tools. They proved that improving the location of a workpiece can decrease the actual cycle time on the machine, down to 40%. In another study, Yang et al. [3] draw attention to effects of the workpiece location on tracking errors of rotary axes due to transmitted cutting forces. They validated that the workpiece location has crucial effects on contouring accuracy for 5 axis tilt rotary table.

Integration of industrial robots with milling processes started in early 1990's. The robots for machining applications evolved from polishing, deburring and grinding to milling. In this regard, it is also shown that use of industrial robots in grinding processes demonstrates several advantages to perform such operations by use of compliant tools [6]. On the other hand, there are certain drawbacks of robotic machining applications such that low accuracy, low repeatability and around 50 times lower stiffness compared to CNC machines due to articulated design. For industrial applications of robotic milling, such drawbacks need to be addressed. Along with this aim, researchers studied with related topics. Zhang et al. [7] showed that the performance of the industrial robots for machining applications can be improved through analytical modelling. In their study, the stiffness model of an industrial robot generated to specify cutting force induced displacements and real-time compensation and material removal rate (MRR) control algorithms developed to increase surface finish quality and productivity. In another similar study, Klimchik et al. [8] aimed to increase accuracy and with a more sophisticated stiffness model and error compensation methodology, then evaluated the KUKA robot family [9] in terms of industrial standards for machining applications and confirmed by experiments.

Workpiece location significantly affects the surface quality and machining tolerances in robotic milling, as well. Dumas et al. [10] studied workpiece location optimization considering the stiffness model of robot and the cutting forces with additional redundancy of the 6th axis of the robot to improve machining quality objective defined in their paper. The researchers used a hybrid optimization approach in selection of the workpiece location in robotic machining and compared 4 case scenarios to prove that the best case can have 14 times better results in terms of machining quality. In another study, Vosniakos et al. [11] aimed to optimize of the robot placement using two different generic algorithms that consider dynamically in terms of maximizing the manipulability and minimizing or optimizing the variation the joint torques during a cutting operation they achieved considerable improvement. Similarly, Lopes et al. [12] used a generic algorithm to find best location of the workpiece for different objective functions such as energy consumption and stiffness however the researchers have not considered the specific issues such as chatter and process forces.

Manipulability and stiffness performance of the robots highly dependent on the posture, which is strictly related to the workpiece location. Therefore, optimization of the workpiece location provide better performance in robotic machining applications [13]. Yet, most of the research to adapt and optimize robotic machining applications considers stiffness characteristics and aimed error compensation, on the other hand not all robotic machining applications exposed to high process forces such as grinding and polishing. These operations are costly and must be performed on optimal conditions. Therefore, this paper investigates the effect of workpiece location for a toolpath for robotic 5-axis milling operations to improve accuracy. The rest of the paper organized as follows; in section 2, brief information is given about the kinematics of the 6-axis articulated manipulator. Next section explains investigation approach and selection of the workpiece location. In the section 4, the simulations take place to evaluate case studies. Finally, In section 5 conclusions are given.

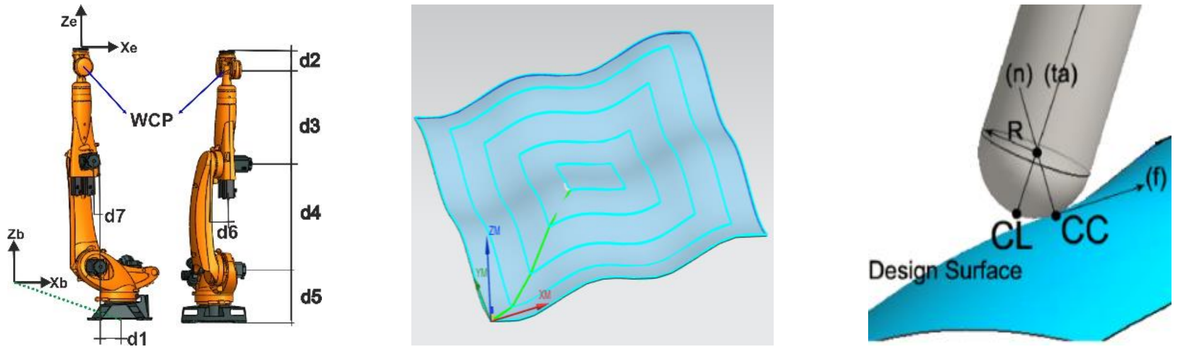
2 Kinematics of 6-axis Serial Arm Robots

Robot manipulator is composed of a set of a links connected mostly by revolute and prismatic joints. A robot with n joints consists of n+1 links. In this research, KUKA KR240 R2900 6-axis serial arm robot was used as machine tool. There are mainly two different spaces such as cartesian and quaternion space used to perform forward and inverse kinematics of the robot and many ways to represent coordinate transformation between joints. Forward kinematics mostly treated by using traditional transformation matrices by Denavit-Hartenberg method [14] which requires less computational load. Forward kinematics is relatively simple due to simple matrix calculations between coordinate systems of the joints. However, inverse kinematics have more computational load caused by highly non-linear equations, kinematic redundancy and singularity issues [16]. In analysis of the effect of workpiece location on the robot movement, inverse kinematics is required, which is briefly discussed in this section.

2.1 Inverse kinematics

Inverse kinematics refers to equations that are used to transformation from the workpiece cartesian coordinates of the end effector to the joint space in angles. In this paper, an analytical solution [17] was adopted to solve the inverse kinematic problem for the serial manipulators with ortho parallel basis spherical wrist. By applying the decoupling method of Pieper [15], the inverse kinematics problem divided into positioning and orientation problem unlike the conventional Denavit Hartenberg method [14]. The solution method consists of 7 design parameters that are available on most of the manufacturer datasheets. The method starts with the solving of the wrist center point (WCP) location. The desired pose of the end effector is given with a $\boldsymbol{U_0}$ 3x1 position vector and 3x3 rotation matrix. $\boldsymbol{R_e^o}$. To determine the position of the WCP, the distance d_2 (see Figure 1a) with the same orientation of end effector is subtracted from the position matrix. After determining the position, the 4 possible solutions respectively elbow up, elbow down and their negative and positive angle combinations can be calculated by geometrical approach. Then the three joints of spherical wrist need to be oriented to achieve the desired orientation. $\boldsymbol{R_e^o}$ describes the desired wrist orientation in Equation (1). Later, determination of all the wrist configurations with first set of solution combinations provide us total 8 possible solutions.

$$\boldsymbol{R_e^c} = \boldsymbol{{R_c^0}^T R_e^0} \tag{1}$$



(a) Parameters for robot (b) Cutting pattern (c) Tool path computation

Figure 1. Robot kinematics and tool path computation.

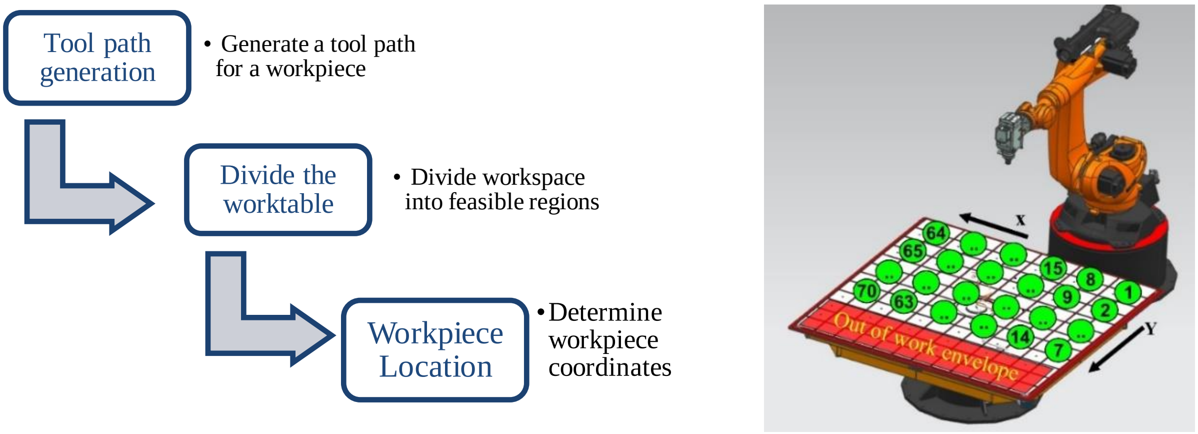
3 Analysis Approach

The effect of workpiece location is analysis by considering the total rotary movement of the axis as metric. Along with this approach, it is aimed to minimize the total axis movement of the joints throughout the tool path. For such a purpose, the inverse kinematic problem is solved for the cutter location (CL) points in the tool path, by changing the workpiece location in an organized fashion. The worktable equally divided into number of areas. In this section, the mentioned approach is explained in detail and results are discussed.

3.1 Tool path generation

In multi-axes milling, tool path generated with cutter contact (CC) data gathered from the computer aided design (CAD) model of the workpiece/surface. The tool path generation is performed on Siemens NX12 ©, where the robot motion is also verified together with post-processing to command the robot. In 5-axis milling, the tool axis should be defined together with the cut direction and the tool path pattern. All of these parameter set may converge to a different preferable workpiece location.

In order to analyze the effect of workpiece location on robotic kinematics, inverse kinematics problem is solved for the same tool path by placing the workpiece on equally spaced locations on the worktable (see Figure 2b). To determine number of workpiece location areas, the reach distance of the robot on the rotary worktable are divided to bound-box of the toolpath. Therefore, the X axis separated in to 10 equal part, Y axis separated in to 7 equal part. Overall, 70 locations on the worktable are generated. The cost defined as the angles covered to reach between consecutive CL points which calculates the overall cost to complete a cutting step of a tool path for a given position of the workpiece and analytically find the best coordinates of it with an input of the X and Y range of the workpiece table. The cost calculation starts from the first point of the toolpath.

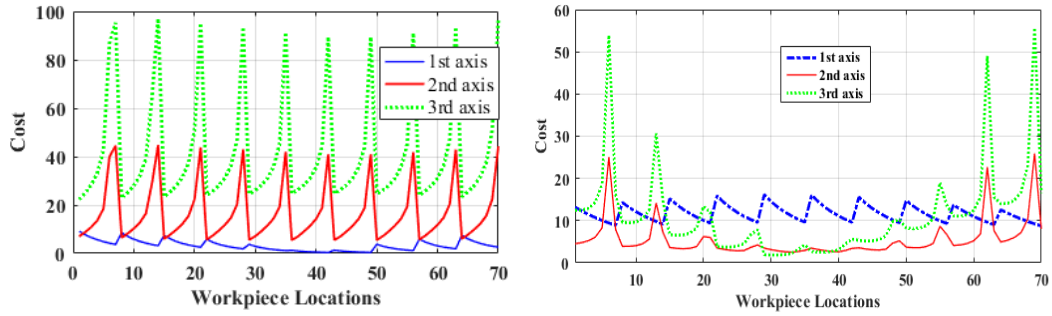


(a) Flow chart (b) Alternative workpiece locations

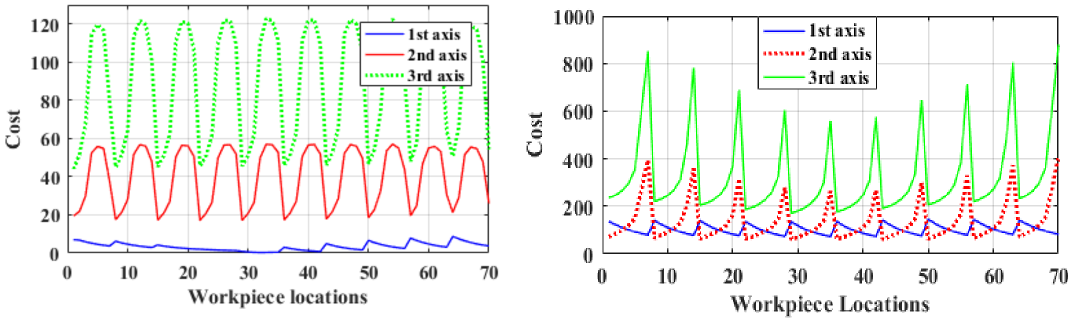
Figure 2. Analysis approach for workpiece location.

4 Simulations

The simulations are conducted for different case scenarios, firstly the tool path generated with a constant tool axis (lead-tilt angles) and simulated for X and Y feed direction. In the Second case, selection of the workpiece location for a varying lead-tilt angle along tool path and last case, the follow periphery cutting pattern effect on workpiece location selection. The variation of robot axis movement with the workpiece location are shown in Figure 3.



(a) Feed direction X (b) Feed direction Y



(c)Varying tool axis (d) Different cutting pattern

Figure 3. Simulation results

For the cases 1-4, to obtain better conditions on the axis motion, better workpiece localization can be identified in X and Y axis coordinates. Figure *3*a shows that when the tool path is along the X axis of the manufacturing coordinates, the movement of the robot's 1st axis strongly depends on workpiece location. However, when the tool path direction is selected along Y axis, the workpiece location significantly affects the movement the robot's 2nd and 3rd axis but not the 1st axis, which is due to the kinematics and the configuration of the robot as mostly the second and the third axes manipulate the spindle along Y direction. It is also noteworthy to state that the center of the worktable is not preferable when the toolpath is along X direction; due to leverage effect the outermost location along Y axis has the minimum axis usage for the robot's 1st axis.

In Figure *3*b, the feed direction is selected along Y axis, where it is seen that, robot movement essentially depends on the 2nd and the 3rd axes. As a result of the second case, it is observed that the selection of the workpiece location may have diverse influence on particular axes. It can be seen also the selection of Y axis coordinate for the workpiece has crucial effect on the 2nd and 3rd axes usage especially on the marginal areas along X direction of the worktable

The third case investigates the varying tool axis on the location of the workpiece Figure 3c. shows that the X direction does not have a high influence on the 2nd and 3rd axes. As can be seen in the figure, Y direction might have cyclic effect with respect to constant X coordinate. Therefore, to select an optimal location for all three axes the first step is to decide the X position afterwards Y position. The most favorable location of the workpiece with respect the 1st axis is the center of the X axis unlike the previous cases, however Y axis still selected as the outermost point in the reach distance again due to leverage effect.

The last case, shows the effect of a cutting pattern on workpiece location; the cutting pattern is selected as follow periphery. In the simulations shown in Figure 3d, the pattern consists X and Y directions. Therefore, the overall distribution of the axes rotations have similar effects observed in the first two cases. On the other hand, it is clear to see that 2nd and the 3rd axes have excess rotations on the distant marginal areas however the 1st axis has not affected. For a full cutting operation, the rotation angles can be deducted up to 5 times. As a result of these case studies selection of the workpiece location depends roughly on the cutting direction and cutting patterns and tool orientation.

5 Conclusion

In this paper, a method used for a workpiece location optimization for 5-axis milling operations using KUKA KR240 industrial manipulator. Robotic milling offers a large workspace with respect to conventional CNCs therefore it requires determination optimal workpiece location in terms of different criteria. Simulations are used to determine a favorable positioning of a workpiece. The rotary angles that covered between consecutive CL points defined as cost and calculated for an ordinary tool path which has constant tool axis and optimized tool path. Results indicate that for a smooth and continuous tool path the workpiece location plays an important role. The cutting pattern and cutting direction are most important parameters to achieve optimal locations. The results showed that the particular axis rotations can be reduced up to 5 times, leading to potential improvements in accuracy issues.

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