Tool Axis Optimization for Robotic 5-axis Milling Considering Kinematics

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Abstract
Robotic milling is proposed to be one of the alternatives to respond the demand for reconfigurable and cost-effective manufacturing systems. Serial arm robots are mostly use for robotic milling purposes offering 6 degrees of freedom (DOF) motion capability. In 5-axis milling, the tool axis selection is still a challenge, where only geometrical issues are considered at the computer-aided-manufacturing (CAM) packages. In this study, an approach is proposed to select the tool axis for robotic milling along an already generated 5-axis milling tool path, where the robot kinematics are considered to eliminate or decrease excessive axis rotations. The proposed approach is demonstrated through simulations and benefits are discussed.

Keywords: Robotic Milling, 5-axis Milling, Tool path generation, Motion Optimization

1. Introduction

High value manufacturing industries rely on robots in variety of applications such as assembly, welding, painting and machining. Recent developments in machining applications show the importance of flexible environment for effective machining. Industrial robots offer cost-effective solutions in a flexible manner for machining processes contrary to their technical drawbacks for that purpose such as low accuracy and low stiffness compared to conventional machine tools [1] due to their compliant kinematics. Therefore, selection of improved cutting conditions and strategies including parameters, tool path settings, milling patterns is an important and rising research area for flexible machining systems.

The increasing complexity of aerospace and automotive parts with tight tolerances are strong motivations for 5-axis milling, where increased accessibility is used in machining of parts such as turbine blades, impellers and large composite surfaces. The tool orientation is sustained by the so-called lead and tilt angles. Industrial robots offer 5+ DOF motion capability providing one redundant axis to perform a 5-axis milling operation, which needs to be handled considering the robot kinematics and dynamics.

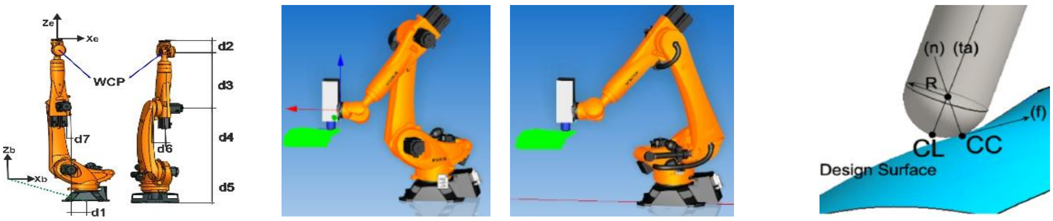
At most 5% of the industrial robots around the world are utilized for machining [2]. To increase their utilization and to make most of the benefit from their opportunities, the research efforts to adapt and optimize the use of industrial robots in machining gained momentum for the last decades [3-6]. Usually, the focal point of these efforts is the compliance and accuracy problems and solving through modelling the kinematics and dynamics of the processes. Dumas et al. [3] and Abele et al. [4] studied modelling of robot compliance using the cartesian stiffness matrix to improve robotic machining operations through finding the optimized posture. In another research Zaeh et al. [5] proposed a model based fuzzy algorithm, which switches the control strategy of the robot depending on the state of the machining process to compensate the static path deviation by considering stiffness characteristics of the robot. Schneider et al. [2] offered a novel method for stiffness based automatic posture optimization for not experts, in robotics. These studies indicate that posture optimization for robots provides drastic improvements on the machining performance. Contrary to such important contributions to the literature, posture optimization especially for robotic 5-axis milling processes, i.e. selection of lead and tilt angles throughout the tool path, still needs investigation.

In 5-axis milling, the additional rotational DOFs to adjust the tool orientation do not only complicate the dynamics and mechanics of the process [7] but also the motion of the robot, which may lead to abrupt axis rotations to meet the desired tool axis vector during the dynamic tool path contouring. In computer aided manufacturing (CAM) the tool axis is usually set by lead and tilt angles with respect to the surface. In the literature, effects of the lead tilt angles on process and CNC machine tools have been studied [6-10]. Marciniak, showed that significant benefits can be made through optimization of tool axis [8]. Choi et al. [9] showed a method for decreased machining time and cusp height by organizing the cutter-location (CL) data by 2D constrained minimization problem formulation by coming up with an analytical expression for cusp height and machining time as a function of lead angle, tilt angle and path interval. In a later study, Makhanov and Munlin [10], aimed to specify optimal sequencing of rotation angles, which additionally contains the uniform distribution of cutter contact (CC) points with respect to rotation angles and weighted overcut and undercut parameters to achieve 70% more accuracy. Recently, Tunc et al. [6] proposed a novel algorithm for 5-axis tool axis selection considering cutting forces, stability and machine tool movements by finding the optimum lead tilt angles for stable cutting conditions on an already generated tool path.

In this paper an approach is proposed to find optimum lead and tilt combinations along a tool path. It is aimed to minimize the axis motion of the robot. Dijkstra's shortest-path algorithm is used considering the combination of CC points on the surface as a connected graph, and the cost function defined as rotation angle of the robot axis while it is travelling between consecutive CL points. Henceforth, the paper is organised as follows, the kinematic solution of the robot is summarized in Section 2. Then fundamentals of tool path computation in 5-axis milling and optimization scheme is explained in Section 3. The application of the approach on a representative tool path is demonstrated through simulations in Section 4.

2. Robot Kinematics

Articulated robots consist of serial links assembled on top of each other by revolute joints from base to the end effector. Robot kinematics refer the analytical solution of the angular joint values to achieve a point in space at the desired orientation of the end effector. Usually, Cartesian and quaternion spaces are used in transformations from process coordinates to the robot coordinates. The rotations can be represented by Euler angles, Gibbs Vector, axis angle, based on 4x4 orthonormal matrices matrices [11]. Henceforth, the inverse kinematic solution adopted to consider robot movements in tool axis selection is explained.



(a) Robot kinematics and alternative solutions (b)Tool path computation.

Fig. 1: Robotic 5-axis milling.

2.1 Inverse Kinematics

In this paper, the inverse kinematic solution approach proposed by Brandstötter et al. [12], valid for almost all of the serial robots with spherical wrist configuration, is adopted. The proposed approach requires 7 geometrical parameters directly measured on the geometrical model of the robot. In this study, KUKA KR240 R2900 robot is used as the machining unit. The 7 geometrical parameters, are defined with respect to the home position of the robot in the base and end-effector coordinate systems defined as demonstrated in Fig1. The last three rotation axes of the robot intersect at a point called as wrist centre point (WCP) therefore for simplicity the robot structure is decoupled [12] to solve the inverse kinematics. So that, the inverse kinematic problem is solved independently by dividing the problem into positioning and orientation. The coordinates of the WCP determined by subtraction of the length between the 4th and 6th joint with respect to given orientation vector from the tool centre point. There are 4 possible solution for positioning the WCP such that elbow-up, elbow-down, and their positive negative angle combinations (see Fig.1). In every feasible solution, to position the last three joints must be adjusted for the given orientation of the end-effector. To determine the robot orientation, wrist must be oriented with respect to WCP for a given position alternative. The coordinate frame of WCP is rotated with respect to base:

$$\boldsymbol{R}_e^c = \boldsymbol{R}_c^{0^T}\boldsymbol{R}_e^0 \tag{1}$$

where, $\boldsymbol{R}_e^0$ represents the desired orientation of the wrist, including rotations around X, Y and Z axis for the WCP.

3. Tool axis optimization approach

In this section the tool path calculated, and the shortest-path graph created for Dijkstra's algorithm, then rotation angle between nodes defined as cost function. After setting the network of the algorithm the optimum lead tilt angle for a cutting step identified. Lastly, recalculation of tool path scheme explained.

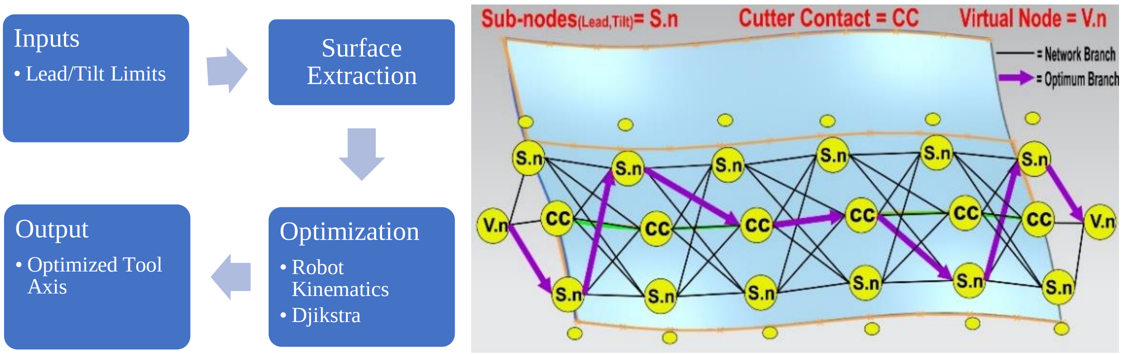
3.1 Tool path computation

Tool path computation requires the path topology and strategy to be known. After determining the CC points according to the point density, the cutter location (CL) point are calculated for known surface normal, **n**, and tool axis, **ta**, vectors as shown in Fig. 1b. The tool axis vector is calculated as concatenated rotations of the surface normal vector around cross-feed, **cf**, and feed, **f**, vectors by lead and tilt angles, respectively. Then, the corresponding CL point is calculated as follows;

$$\boldsymbol{CL} = \boldsymbol{CC} + \rho.(\boldsymbol{n} - \boldsymbol{ta}) \tag{2}$$

3.2 Dijkstra's network for tool path optimization

The generated tool path to machine the surface can be considered as a directed, connected network, where all the CL points need to be visited keeping the end effector at the desired orientation will be generated on the part surface in CAM software. (Fig.2) The part surface properties that used to calculate orientation of tool and location analytically extracted from the CL file of the CAM software.



(d) Flow diagram of optimization (b) Tool path representation by Djikstra's network

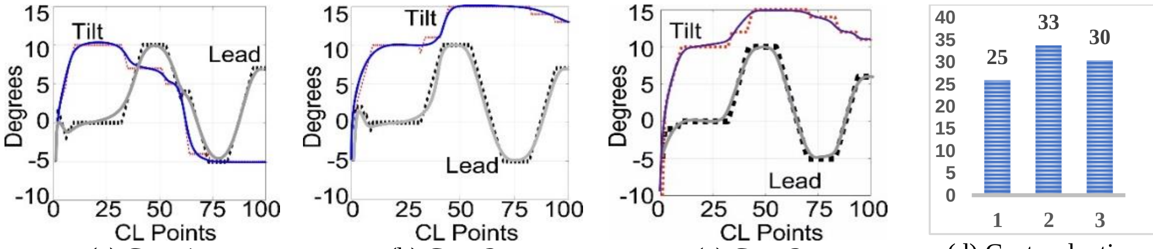
Fig. 2: Optimization approach

In 5-axis milling, tool axis selection directly related with motion optimization of the robot due to serial kinematic chain of the structure. Therefore, it is the main criteria of our optimization approach. The aim of this study is avoiding from excessive rotations caused by wrong tool axis selection and minimizing the rotary motion on the robot axes. To optimize the motion of the manipulator within a range of lead and tilt angles, Dijkstra's shortest path algorithm, which is suitable for finding the shortest for an interconnected graph from a source node to a sink node used. In particular, for machining applications, nodes of the algorithm defined as cutter contact points. Algorithm seeking for shortest path for a given toolpath by calculating every lead tilt combination for every CC point sub-nodes. However, Dijkstra's algorithm determines the shortest path for a given network without considering the internal loops and path direction and node continuity.

Application of Dijkstra's shortest path search algorithm requires networks setting to create continuous tool path for machining. The other network modification for Dijkstra's algorithm that taken account in our approach, is the shortest path direction sticks to the feed direction to prevent cyclic motion between sub-nodes. The sequence of the sub-nodes defined with respect to given lead and tilt angle range. The cost function defined the angle difference between two consecutive CL nodes. The algorithm seeking for minimum rotation angles for given path by using our modified Dijkstra's shortest path method. Even tough for a relatively small cutting step that consist of 100 CC points, possible lead, tilt angle combinations around 10 million. Yet, this number depended on the angle range and search increment in the algorithm.

4. Case Study

To mimic the real constraints in a machining scenario, specific lead/tilt angles are defined for particular CL points, i.e. lead 0, tilt 10 degrees. Four cases are compared through simulation, which are (i) for the first three axes, (ii) last three axes and (iii) all axes, (iv) constant tool axis selection, respectively. In tool axis optimization, the ranges for lead and tilt angles are set as -5 to 10 degrees, and -5 to 15 degrees, respectively. Fig. 3 shows that the rotational cost can be reduced significantly by tool axis optimization.



(a) Case 1 (b) Case 2 (c) Case 3 (d) Cost reduction

Fig. 3: Comparison of simulation cases.

Results indicates that instead of using constant lead and tilt angle, optimized lead and tilt angles can reduce the axis rotation up to 30% compared to the constant lead-tilt selection of 0 and 10 degrees, respectively.

5. Conclusions

In this paper, optimum tool axis selection to minimize the axes rotation of an articulated manipulator KUKA KR240 R2900 carried out for a single cutting step of a predefined tool path for 5-axis surface milling. The angle difference between two consecutive CL points, defined as the cost to optimization algorithm. Shortest path algorithm seeking for optimum lead and tilt angles of every CL point for a given cutting step. Results show that optimization of the tool orientation can reduce the rotation of the axes up to 30%.

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