Virtual Engineering: Model based Off-line Programming Method for Industrial Robot

Xingguo Yin, Li Tao
ABB Corporate Research China
No. 31 Fu Te Dong Dan Rd., Waigaoqiao Free Trade Zone, 200131
Shanghai, P. R. China
xingguo.yin@cn.abb.com，Matrix-li.tao@cn.abb.com

***Abstract*—this paper introduces the basic knowledge of machining process and compares the traditional methods of off-line generating tool paths from surface of a CAD model. Based on that it comes up with a model for machining procedure and then a pattern based programming method is demonstrated; it also discusses target orientation adjustment and an algorithm for how to set spin angle according to the given tool working range is presented.**

***Keywords*—path generation, industrial robot, off-line programming, machining**

I. INTRODUCTION

Machining application is a target intensive application, and it's always time consuming to program for tool paths online. Polishing and grinding are two typical applications in machining area. The common feature for the two applications is that large number of targets is created from the surface of work pieces. It's a trend to move the online programming to off-line programming to save time and improve the accuracy of tool paths.

A lot of research work has been done for off-line generating tool paths,; generally there are 3 types of methods to generate tool paths: ISO-parametric line machining, intersecting line machining, projecting line machining[3-10].

ISO-parametric line machining: some surfaces, for example spline surfaces, can be represented by 2 parameters. If one of the parameter is fixed, an ISO-parametric line can be calculated and the tool path is generated along the ISO-parametric line, see Figure1. Since the tool path is along the ISO-parametric line, the trajectory of tool is inline with the nature of the surface and machining result is sometimes better than other methods. This method requires that a surface can be represented by 2 parameters and the distance between 2 lines should be consistent.

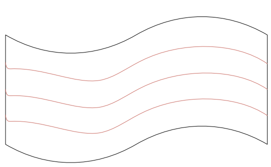

Figure 1. ISO-parametric line

Intersecting line machining: By intersecting a surface with a series of planes so called cutting surfaces, a series of intersecting curves are created and tool paths are generated from intersecting curves. The cutting planes can be parallel to each other or the orientation of cutting planes can be changed to adapt to a specific application; and the offset between 2 cutting surfaces should be adjusted according to the width of tool trajectory. This method is very reliable, but for a complex surface it is a challenge to set the orientation of cutting planes.

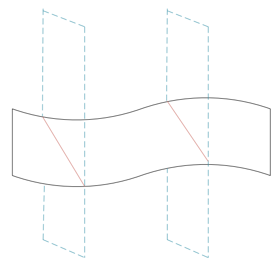

Figure 2. Intersecting line machining

Projecting line machining: By planning tool paths in 2D-plane and then projecting planned paths to the surface of CAD model, a projecting line can be attained to generate accurate tool paths. The strength of this method is that the shape of the region to be worked with can be considered during path planning. This method is useful for regular surface, but for the irregular surfaces whose curvature changes a lot from side to side, this method doesn't work well.

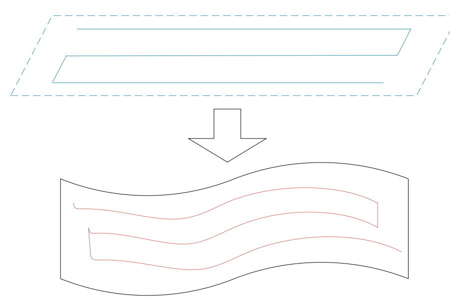

Figure 3. Projecting line machining

The above methods are widely used in generating tool paths for CNC machines, but there are no mature products focusing on off-line programming for 6-axis industrial robot, current work is aimed at giving a systematic way of off-line generating tool paths for 6-axis robot. The method presented here has been verified based on ABB off-line programming platform – RobotStudio.

II. BASIC DEFINITIONS IN MACHINING PROCESS

Polishing, grinding, deburring, cutting and etc are the conventional applications in machining area, and this paper is aimed at polishing and grinding applications and gives an approach of generating tool paths from the surface of CAD models. Compared with CNC machines and 3-axis robots, a 6-axis industrial robot have more freedoms and not only path location should be considered, but also the orientation of tool path should be considered [11].

A. *Tool Definition*

Tools used to polish the surface usually can be categorized two types, face polishing tool and side polishing tool. These 2 types of tool look similar in the shape, both of them have a spindle, which turns around in high speed during working. For face polishing tool, there is circular plate at the end of spindle, it’s the face of plate contacting with work pieces; for side polishing tool, and there is a wheel at the end of spindle and the edge of the wheel contacts with work pieces.

Each tool has a center point so called TCP which contacts work piece during working, and a tool path is a trajectory of TCP.

TABLE I. TOOL AND TARGET DEFINITION

Term	**Definition**
Face Polishing Tool	A tool whose contact area with a work piece is vertical to tool spindle
Side Polishing Tool	A tool whose contact area with a work piece is parallel to tool spindle
Target	A position in 3D space for robot moves to, when robot arrives at this position, the TCP current frame should be the same as target frame

B. *Tool Posture Definition*

Tool path is a collection of robot targets, while each robot target can be described as two 3-dimension vectors: translation vector and orientation vector; a translation vector tells robot which location that a tool should be moved to and an orientation vector tells what posture should be when a tool reaches the location. A translation vector and an orientation vector can compose a 4 by 4 matrix, so called frame; any combination of rotation, translation of a robot target can be described by such a frame.

In order to easily describe and adjust tool’s posture at a robot target, an important concept: reference coordinate system [RCS], is imported. RCS is a frame representing translation information and orientation information. Each robot target has a specific RCS, which locates on the surface and the orientation is bound with path direction and surface geometry feature, as shown in Figure 4.

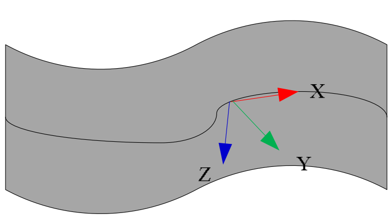

Figure 4. Reference Coordinate System

According to Euler’s rotation theorem[1][2], any rotation can be described using three angles so-called Euler angles and a transformation frame of rotation can be converted into Euler angles. There are several conventions for Euler angles, depending on the axes about which the rotations are carried about. Here a so-called “XYZ-convention” is used, and the rotation is defined by Euler angles (φ, θ, ψ), where the first rotation is by an angle φ about the x-axis, the second is by an angle θ about y-axis, and the third is by an angle ψ about z-axis.

The rotation frame from RCS to a robot target frame can be converted into Euler angles. Since these 3 angles are the reflection of tool posture, three intuitive names are given to them, as shown in TABLE II. Thus the adjustment of tool posture can be achieved by adjusting travel angle, work angle and spin angle. Figure5, 6, 7 describe the meaning of these 3 angles.

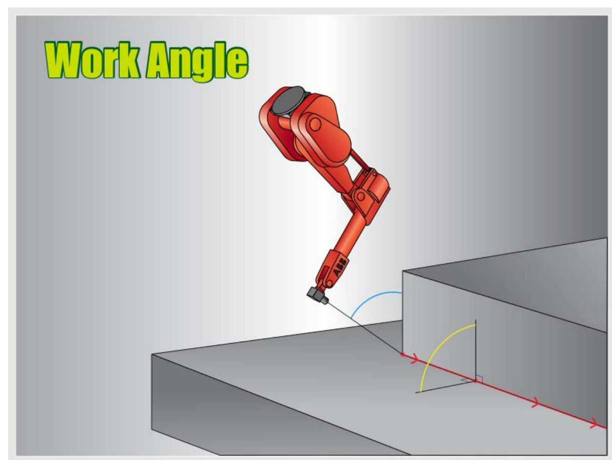

Figure 5. Work Angle

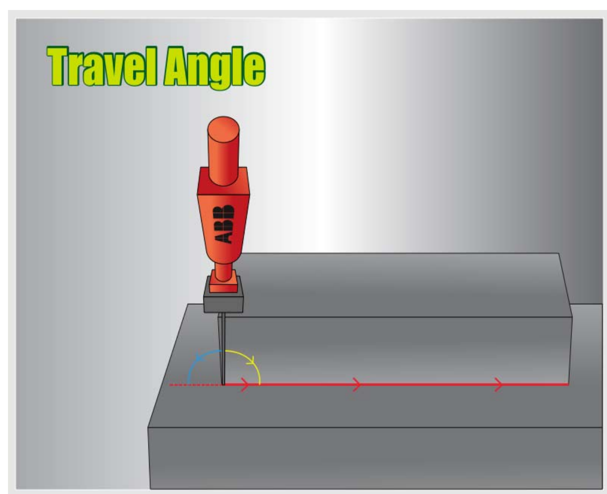

Figure 6. Travel Angle

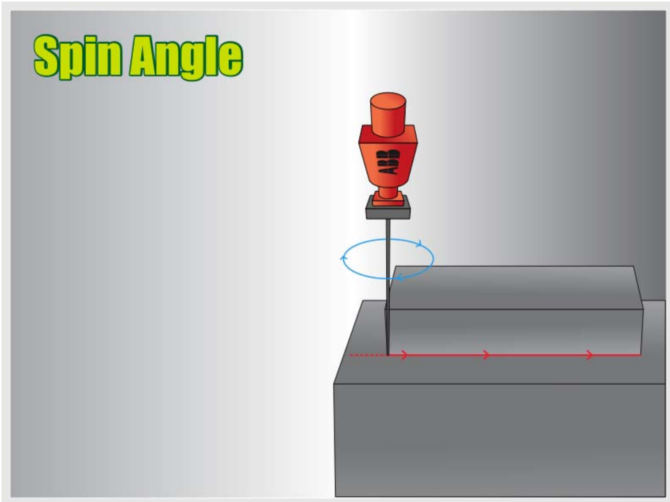

Figure 7. Spin Angle

TABLE II. TOOL POSTURE DEFINITION

Term	Definition
Reference Coordinate System	A reference frame used to help describe the transformation of a tool's posture and position, the location of this frame should be at surface; and posture or orientation is as below: X axis same as the path direction, pointing to next target Z axis is located at the surface normal of the position, but points inside of a work piece Y axis is the result of Z axis cross X axis
Travel Angle	A rotation angle θ about Y –axis, it reflects the angle between tool spindle and path direction, θ € [0,π]
Work Angle	A rotation angle φ about X-axis, it reflects the angle between tool spindle and surface, φ € [-π/2,π/2]
Spin Angle	A rotation angle ψ about Z-axis, it reflects the rotation of tool spindle, ψ € [0,2π]

III. MACHINING PROCESS MODELING

The method presented here is aimed at polishing and grinding applications, the common points in both of these applications are listed as below:

- Tool paths are generated from surface
- Usually a tool path has the following 3 parts: Leading, Machining, Leaving
- A path might have several sections if there are holes or gaps in the path direction
- Usually a linear movement is used to approximate an irregular surface, a tool path is composed of several straight lines

According to the common points above and engineering experience, a robot motion model for 6-axis industrial robot is given as below.

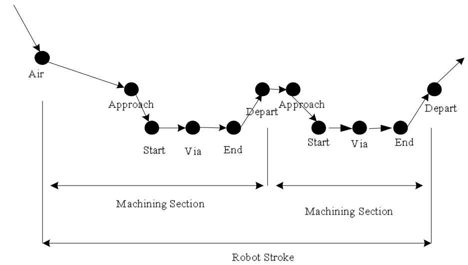

Figure 8. Robot Motion Model

A machining procedure is a flow that a robot goes through all PASSes, which are arranged in a certain sequence; a PASS is a tool path, which starts from one side of surface and ends at the other side of surface. A PASS contains one or more machining sections; each machining section has 5 or 6 motion parts in the sequence of air part, approach part, start part, via part, end part. Figure 8 describes the whole model.

In this model, air part is a collection of several robot targets where the speed might be fast and motion type of robot can be linear or joint, the purpose of this part is that robot can quickly move close to a work piece; Approach part leads robot to move to surface smoothly and safely; Start part is the first target that locates on surface, where some signals or events can be triggered for cell synchronization; Via part contains the targets located on surface and materials will be removed at this part, and the motion type for this part should be linear; End part is the last target located on surface and it's also a synchronization point to trigger signals and events; Depart part tells robot how to leave a surface.

IV. PATTERN BASED PATH GENERATION

In machining process model, the most difficulty is that how to generate targets between start part and end part. Due to the complexity of surface, it's hard to find a general solution that is suitable for all surfaces. Based on the traditional ways, a pattern based method is suggested here. A pattern is a kind of algorithm to generate tool paths from surface of a CAD model. One pattern is suitable for several types of surface. Before generating tool paths a proper pattern should be selected according to the feature of a surface.

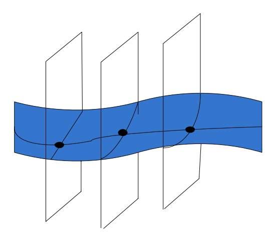

Figure 9. Cutting plane along feature line

Pattern 1: Cutting plane along feature line

As shown in Figure 9, feature line is a curve, which reflects the geometry feature of a surface; feature line is faceted to several points according to tool width and path overlap rate; a series of cutting planes are created at these points and the normal of cutting planes is the same as feature line tangent at this point. The intersection between cutting planes and surface will be the machining section in tool paths.

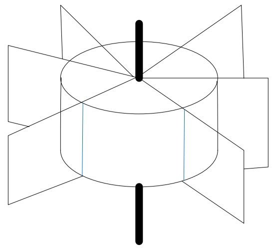

Figure 10. Circular plane cutting

Pattern 2: Circular plane cutting

For this pattern a center axis and a radius should be specified, and a circle is created and faceted into points. Cutting planes with the normal equal to the tangent of this circle line are located on these points. This pattern is suitable for rotational surface, as shown in Figure 10.

Pattern 3: ISO-parametric line

As described in Figure 1, this pattern only works for the surface that can be represented by 2 parameters. Spline surface is a kind of this type, for other types, this pattern doesn't work.

By applying a proper pattern, curves will be generated on the surface and the targets between the start and the end can be generated from these curves. Since most of 3D engines, for example ACIS, support faceting a curve to points, the topic of how to get targets from a curve will not be discussed in this paper. The approach/depart targets can be added according to start/end targets. Figure 11 gives a real example, in which the tool paths are generated by pattern 1.

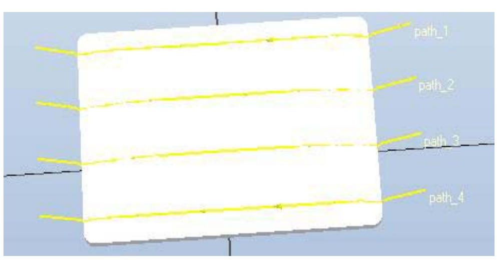

Figure 11. Tool paths generated by Pattern 1

V. TARGET ORIENTATION ADJUSTMENT

By default all the targets have the same orientation as their respective RCS, with all 3 angles (travel angel, work angle and spin angle) having the value of 0. Sometimes the orientation of a target needs to be adjusted due to application requirements, such as the type of tools and robot motion. With the concept of 3 angles, it's easy to understand and adjust a target's orientation.

For a face polishing tool, usually the spindle is not 100% vertical to the surface; instead the spindle tilts with a little angle. As shown in Figure 12, this can be achieved by setting the travel angel to a specific value α

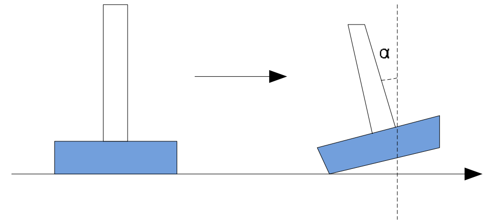

Figure 12. Travel angle adjustment

For a side polishing tool, the work angle for all targets should be adjusted to 90 degree since the spindle is parallel to a surface during working.

By default a target has the same orientation as its RCS and X-axis of target points to path direction. For a 6-axis industrial robot, each axis has a limited rotation range, and if a path direction changes too much, some targets might be not reachable. As shown in Figure 13, the spin angle for 3 targets is 0, which makes robot itself have to rotate a lot to reach these targets during movement. This problem can be eliminated or reduced by spin angle compensation since the changing of spin angle doesn't affect the machining result. In Figure 14 the spin angles for 3 targets are -30, 0 and 30 degree and rotation of robot itself is greatly reduced. Usually a machining tool or a work piece is mounted on the 6th axis of a robot, and spin angle compensation can reduce the rotation of 6th axis of a robot.

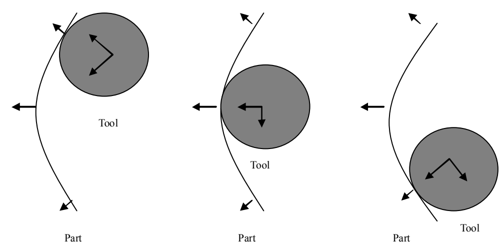

Figure 13. Spin Angle(0, 0, 0)

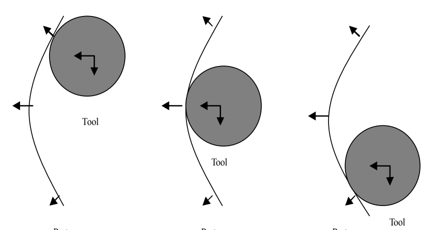

Figure 14. Spin Angle(-30, 0, 30)

The adjustment range for spin angle is called tool working range. For the case that robot holds a tool, the tool working range usually is 360 degree; but for the case that robot holds a work piece, the tool working range is usually less than 360 degree. Here a simple algorithm is presented to set spin angles for all the targets in a path according to the given range of spin angle. In this algorithm, the middle target of the path is selected as the reference target, whose spin angle is 0, and the spin angles for rest of targets are smoothly distributed in the given tool working range.

$$\alpha_i = \psi \times (L_i - L_m) / L \quad (1)$$

$$L_i = \sum_{j=0}^{i-1} Distance(j, j+1) \quad (2)$$

$$L = \sum_{j=0}^{n-1} Distance(j, j+1) \quad (3)$$

Where ψ is the allowed spin angle range; α_i is the spin angle for target i, m is the index of target which is located in the middle of path, n is the total number of targets, L_i is the length from first target to target i, L is the total length of the path. Distance (j, j+1) is the length between target j and target (j+1). Figure 15 is an example for spin angle adjustment, in which the tool working range is 360 degrees.

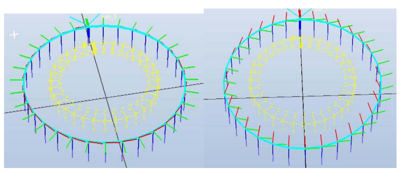

Figure 15. Path before and after spin angle adjustment

VI. WORK FLOW FOR OFF-LINE PATH GENERATION

In order to get ideal tool paths, a lot of information should be considered, such as process parameters, tool and work object information, algorithms and etc. A procedure for path generation is given here.

A. *Define surface*

Surface is the area to be polished; it contains one or more small faces.

B. *Define Process parameters*

Process parameters are the information related with path accuracy and polishing speed. Usually a surface is approximated by several straight lines, and the tolerance and deviation angle should be specified for path generation.

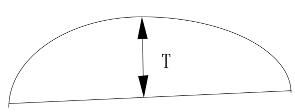

Figure 16. Tolerance

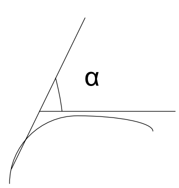

Figure 17. Deviation Angle

Tolerance is the allowed maximum distance between a curve and the corresponding straight line.

Deviation angle is the allowed angle between the tangents of two linked targets

C. *Define tool and work object information*

Tool information should be specified. Normally tool information contains following points:

Tool type: side polishing or face polishing.

Tool width: the width of the contact area with work piece.

Tool overlap rate: how much the tool paths are overlapped with each other.

TCP: tool center point

Work object is the coordinate information for all the targets, and all the targets are related to a work object and later on when tool paths are deployed to a real cell, only the work object needs to be calibrated.

D. *Define path and target information*

Path information includes the styles how two linked paths are connected and there are usually two types of connection styles and they are sweeping and clipping as shown in Figure 18.

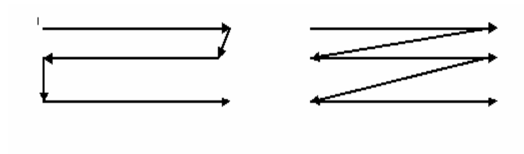

Figure 18. Sweeping and Clipping

Target information contains the information of target offset and target orientation. The offset to RCS, the work angle, travel angel and spin angle should be specified before path generation.

E. *Select a proper pattern*

A pattern is an algorithm to generate curve from surface of a CAD model. A proper pattern should be selected for a specific surface. After a pattern is selected, a series curves will be generated on a surface, and tool paths can then be generated from these curves.

F. *Configuration and simulation*

A configuration is a combination of rotation degrees of 6 axes. For a 6-axis industrial robot it's possible to have several feasible configurations for a same robot target. However for the whole tool paths, a correct configuration for each target should be picked out to ensure that robot move smoothly from the first target to the end.

After setting configurations for all tool paths, a simulation for all paths should be carried out. RobotStudio provides such a function to simulate robot behaviors in virtual world. If no problems found during the simulation, all tool paths are ready to deploy to a real cell.

Figure 19 is an example of off-line path generation. In this figure a cylinder surface is selected to be polished by a side polishing tool. The tolerance is set to 1 mm, tool width is 50 mm and the pattern of cutting plane along feature line is selected.

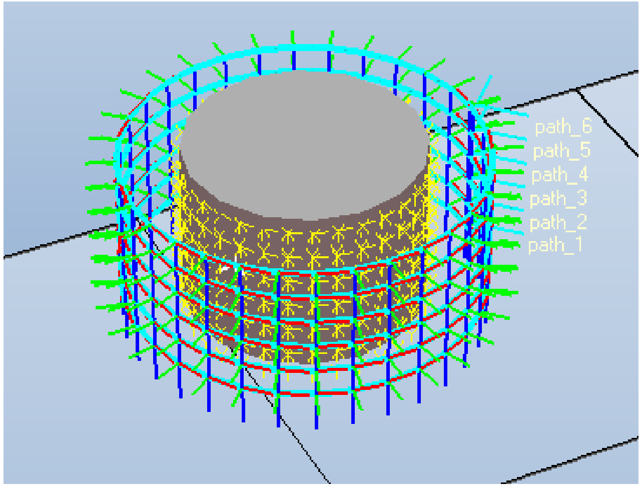

Figure 19. Example

VII. SUMMARY

In this paper, a model for machining procedure is introduced. A machining tool path can be described as a combination of several motion sections: air move, approach, start, via, end and depart. A pattern based off-line programming method is demonstrated and three patterns to generate tool paths from surface are explained. A target orientation can be described as travel angle, work angle and spin angle. By adjusting these angles the orientation of a target can get updated. An algorithm of spin angle compensation is presented, with which the rotation of robot is reduced and reach ability of target is improved. The method presented in this paper is now used in ABB off-line programming tools. With the help of these tools the programming time for a complex work piece is reduced from several days to a couple of hours and mean while the path accuracy is greatly improved.

REFERENCES

[1] http://mathworld.wolfram.com/EulerAngles.html
[2] http://gpwiki.org/index.php/3D:Matrix_Math
[3] Hamura masayuki, Aztuma Kenji, "Method for off-line teaching of robot", European patent, G05B19/425
[4] Skeeters Clifford M, Benjamin Chris W, "Method of generating grinding paths from a computer model for controlling a numerically controlled grinder", European patent, G05B19/4099
[5] Higasayama Harushisa, Kubota Mitsuru,"Cutting path generation method for operating NC machine with CAD/CAM control", European patent, G05B19/4097, G05B19/41
[6] Maenishi Hiroaki, ":Industrial robot off-line teaching method", Japanese patent, JP6226665
[7] Saito Masaru, Kuragano Tetsuzo, "Method for preparing free curved surface", Japanese patent, JP6168302
[8] Ban Kazukuni, Sato Takayuki," Finish machining device", European patent, G05B19/416A
[9] Sumi Masanobu, Marumoto Seiichi, "Grinding method by grinding robot", Japanese patent, JP7052036
[10] Kadono Mitsuhiko,"Machining-related information generating apparatus and numerical controller having the same", European patent, G05B19/4093
[11] ABB Robot User Manual, "RAPID Reference"