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Trajectory Optimization of Composite-pipe Cutting Based on Robot

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Abstract

The industrial robot with 6 degree of freedom is studied in this paper. According to the interference problems that exist in the actual cutting process of robot, a method is proposed which could make optimal selection of the trajectory of robot after the interference problems is eliminated. After the determination of the posture of cutting head, the model of intersecting line and programming the cutting trajectory of robot, the 3D model of mechanical arm and incised work piece are imported into OPENGL, using collision detection based on OPENGL to screen the interference point of the robot arm. The cutting trajectory is verified through the simulation with ADAMS. The simulation result shows that the robot can run steadily after eliminating the interference and the intersecting line meets the demands.

Keywords: *industrial robot; intersecting Line; trajectory planning; interference point*

1. Introduction

Currently composite material has become a very important technology industry, and in the related industry the using of composite-pipe intersection cutting [1] has become more and more important. Since the intersection lines are typical and complex space curve, so hand-cutting and machine-cutting have been used in the pipe cut processing. Since the intersection lines are typical and complex space curve, hand-cutting and machine-cutting have been used in the pipe cut processing. Although hand-cutting is flexible and convenient, shortcomings like poor quality, large size deviation, severe material waste and low efficiency also exists. Cutting machine can reduce labor intensity, but it has large volume, simple function and low accuracy. Compared with the traditional cutting machine [2], robot can reach the high accuracy and realize the cutting of composite materials pipes .And high accuracy of winding forming and grinding can be reached by replacing the ending extensions. The application of robot in intersecting line cutting of composite materials pipes can overcome the shortage of traditional cutting pattern.

Position and orientation interpolated trajectory planning algorithm [3-4] does not meet the demands of composite-pipe intersection cutting. Zeng *etc*. presented a continuous path planning method[5-6] based on Fleiner Space Vector .The method has a weakness of large computing and then increase the difficulty of trajectory planning. As the foundation of the intersection cutting, the trajectory planning of robot directly affects the accuracy and timeliness of cutting and has a great influence on improving the operating efficiency stability and accuracy. Since the fittings and the relative position of the robot are relatively fixed, interference points which are difficult to achieve for the robot during the cutting process will occur, so using a reasonable method to circumvent these points is very important.

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In this paper firstly, we set up the each joint's coordinate system of KUKA robot with six degrees of freedom according to D-H [7] parameter method. Mathematical models of intersecting line and tools pose is analyzed next .Then the cutting path of the robot was planned, and collision detection method based on OPENGL is proposed. Finally the cutting trajectories of robot were simulated using ADAMS.

2. Structure of the Robot

D-H table of each joint of robot is shown as Table 1. θ represents rotation angle about Z-axis. d represents distance between the two adjacent common vertical lines on Z-axis. A represents the length of every common vertical line(joint migration). Angle represents the angle between two adjacent Z-axis(joint torque).

As shown in Figure 1, coordinate frames of robot's links are established according to D-H representation. In Figure 1, coordinate system {O} is the basic coordinate of robot. Coordinate system {B} is robot last link frame. Coordinate system {A} is main pipe coordinate of pipe fittings which is waiting to be processed. As tool tip is fixed in end link, tool coordinate {T} is unchanged compared with location and posture in robot last link frame {B}, but it will be changed because of motion of tool tip in trajectory curve compared with location and posture in main pipe coordinate {A}.

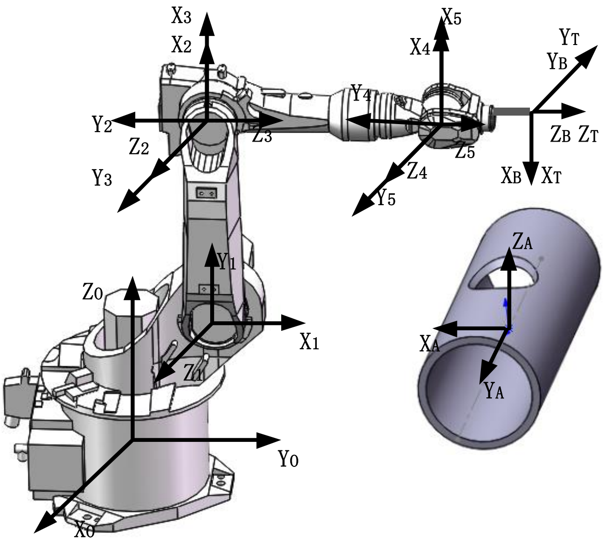

Figure 1. The Joint Coordinates of Robot

#	θ_{i+1}	d_{i+1} /mm	a_{i+1} /mm	α_{i+1}	θ_i
0-1	θ_1	675	350	90°	(-185, 185)
1-2	θ_2	0	1150	0°	(-140, -5)
2-3	θ_3	0	0	90°	(-120, 155)
3-4	θ_4	1200	0	-90°	(-350, 350)
4-5	θ_5	0	0	-90°	(-125, 125)
5-6	θ_6	215	0	0	(-350, 350)

Table.1. D-H Parameters of the Robot's Each Joint

3. Intersecting Lines Mathematical Model and Head Posture

3.1. Mathematical model of intersecting lines

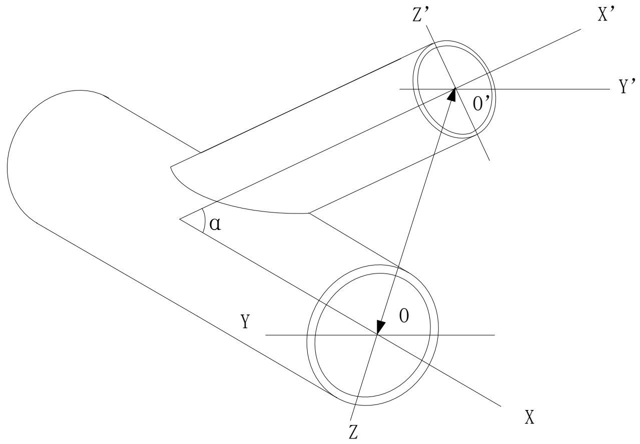

Figure 2. Mathematical Model of Intersecting Lines

In Figure 2, central line of main pipe [8] is assumed as X-axis in coordinate system. Origins of coordinate X, Y and Z are intersection points of projection of central line of branch pipe on X-axis and X-axis, and therefore it can determine YOZ plane. X is central line of branch pipe. Angle between main pipe and central line of branch pipe is between 0° to 180°. Intersection point of YOZ plane and X-axis is origin O' of coordinate X'Y'Z'. OO' is Y-axis of coordinate XYZ. Plane of coordinate XYZ is determined by right hand rule. Y'-axis is through point O' and intersects with Y-axis. In the same way, transformation matrix from plane XYZ to X' Y'Z' in coordinate X'Y'Z' is determined as:

$$T=\begin{bmatrix} \cos\alpha & 0 & -\sin\alpha & 0 \\ 0 & 1 & 0 & 0 \\ \sin\alpha & 0 & \cos\alpha & 0 \\ n\sin\alpha & 0 & n\cos\alpha & 0 \end{bmatrix} \quad (1)$$

Now radius of main pipe is assumed as R, radius of branch pipe is assumed as r. Equation of intersecting Lines which is in the form that is assumed as independent variable and

[illegible] (2)

[illegible] (3)

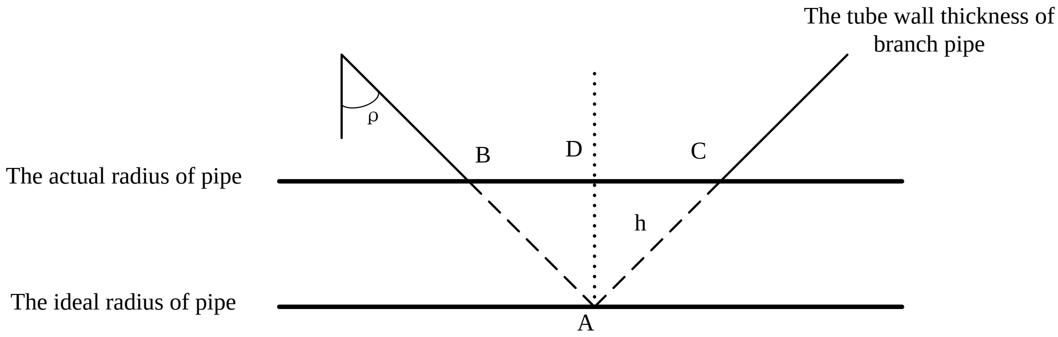

Figure 3. Schematic Diagram of Error Solution

Error of BD can be obtained according to the calculation in the picture

$$\tau_{BD} = \tan\rho h \tag{4}$$

h represents error of pipe thickness; p is dip of cutting tool.

$$\tau_{CD} = \left| X(R, \theta) - R(r, \theta) \right| \tag{5}$$

By adding compensation value which makes error to Equation of intersection Lines directly, Equation of intersection Lines which is used to process can be obtained accurately and optimization of equations can be realized, compensating the whole process. Considering the error of pipe thickness, Equation of intersection Lines in pipes is:

$$[illegible] + \tau_{BD} + \tau_{CD} \tag{6}$$

3.2. Head Posture

To ensure the accuracy of intersecting line and the quality of incision, when we do the three-dimensional cutting, we need to keep the axis of cutting head vertical to the surface of the cut face. The rotation matrix of attitude of cutting head can be described by the cosine that {T} coordinate system relative to {A} coordinates system.

Posture model of the cutting head as shown, Z axis of tool coordinate system is fixed on the axis of the cutting head. In order to make the cutting head posture meet technical requirements, when the origin of tool coordinates (T) moves on the trace of intersecting lines, it’s Z axis must be kept on the surface of the normal vector of the main pipe cylindrical surface. Because the normal vector of the main pipe cylindrical surface is always vertical to the axis of, namely the Z axis of tool coordinates always keeps parallel to the Y axis of the main pipe coordinates. Thus we only need to calculate the included angel of Z axis of tool coordinates and Z axis of main pipe coordinates to confirm the three included angels of three axes of tool coordinates and main pipe coordinates

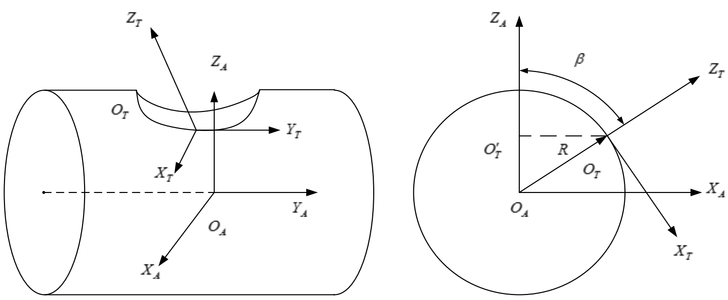

Figure 4. Laser Head Posture Model

Picture 4shown is the main pipe's projection on the $X_AO_AZ_A$ surface (the normal section of cylinder). Making vertical of ZA axis by OT point, O'T is the Point of intersection.

Where

$$|O_T O'_T| = r\cos\varphi \tag{7}$$

We can caculate the value of β is:

$$\beta = \arcsin\frac{r\cos\varphi}{R} \tag{8}$$

By using the random three points on the cylinder (arbitrary two points not on one main lines.) interpolation algorithm of segment position was determined. The starting point of the Euler angle is $Euler(0,\beta,\frac{\pi}{2})$, the ending point of the Euler angle is $Euler(0,\beta,\frac{\pi}{2})$.

4. Robot Trajectory Planning and Optimization

4.1. Robot Trajectory Planning

Robot path planning [9-10] can be achieved by the robot coordinate system transformation between each joint, link the two independent paths. *A* path through robot matrix, namely transform coordinates *O* to coordinates *B* to tool coordinates T, its transform equation is:

$${}^{O}_{T}S = {}^{O}_{B}S\,{}^{B}_{T}S \tag{9}$$

The other path is through the main pipe, namely transform coordinates *O* to coordinates *A* to coordinates *T*, its transform equations is:

$${}^{O}_{T}S = {}^{O}_{A}S\,{}^{A}_{T}S \tag{10}$$

To structure the above two equations to a transform equation, namely

$${}^{O}_{B}S\,{}^{B}_{T}S = {}^{O}_{A}S\,{}^{A}_{T}S \tag{11}$$

First obtain the homogeneous transformation matrix, then calculate the angle values of the robot's six joint. After inputting the joint angle value to the motion control unit the trajectory plan of robot cutting would be realized. To solve the homogeneous transformation matrix ${}^{O}_{B}S$, ${}^{B}_{T}S$ 、 ${}^{O}_{A}S$ 、 ${}^{A}_{T}S$ should be solved at first.

The homogeneous transformation matrix ${}^{O}_{A}S$ that {*A*} coordinate system relative to {*O*} coordinate system is:

$${}^{O}_{A}S = \begin{bmatrix} 1 & 0 & 0 & x_0 \\ 0 & 1 & 0 & y_0 \\ 0 & 0 & 1 & z_0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 & 0 \\ \sin(\theta) & \cos(\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

The homogeneous transformation matrix ${}^{B}_{T}S$ can be written as:

$${}^{B}_{T}S = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

The homogeneous transformation matrix ${}^{A}_{T}S$ can be written as:

$$ {}^{A}_{T}S=\begin{bmatrix} \frac{\sqrt{R^2-r^2\cos^2\varphi}}{R} & 0 & \frac{r\cos\varphi}{R} & r\cos\varphi \\ 0 & 1 & 0 & r\sin\varphi \\ -\frac{r\cos\varphi}{R} & 0 & \frac{\sqrt{R^2-r^2\cos^2\varphi}}{R} & \sqrt{R^2-r^2\cos^2\varphi} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{14} $$

The homogeneous transformation matrix ${}^{O}_{B}S$ can be written as:

$$ {}^{O}_{B}S={}^{O}_{A}S\,{}^{A}_{T}S\,[{}^{B}_{T}S]^{-1}=\begin{bmatrix} -\frac{\sqrt{R^2-r^2\cos^2\varphi}}{R} & 0 & -\frac{r\cos\varphi}{R} & x_0+r\cos\varphi \\ 0 & -1 & 0 & y_0+r\sin\varphi \\ -\frac{r\cos\varphi}{R} & 0 & \frac{\sqrt{R^2-r^2\cos^2\varphi}}{R} & z_0+\sqrt{R^2-r^2\cos^2\varphi} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{15} $$

4.2. Trajectory Optimization Method

Robot trajectory planning includes two aspects: path planning and motion planning. For industrial robot, path planning is very important, and the goal is to make the robot smoothly follow the certain evaluation criteria (such as the shortest path, the best time) to find a starting point from the beginning to the end of the movement path. In this paper, the process of off-line programming is introduced to avoid the interference and singular point of the robot. The 3D digital model of the robot and the end spindle is imported into OpenGL [11-12] by using OpenGL. If it has, ADAMS simulation can be used to verify and the optimal path can be solved by means of the rotating end tool attitude (because the rotation movement of the spindle axis is not affected by the milling process).

5. Examples for Simulation Calculation

Matlab is used to compile the robot kinematics algorithm, and solve the forward kinematics of the terminal joint coordinate $\{O\}$ and the tool coordinate $\{T\}$. The variables in the homogeneous transformation matrix should be divided into 5000 sampling points, and they are the 5000 steps of intersecting line trajectory simulation. Set R=150mm and r= 100mm and get the inverse kinematic solution. And then the angle of each joint of robot were substituted to the end of the robot joint coordinates $\{B\}$ and the tool coordinates $\{T)$ of the forward kinematics solution, considering that collision detection of singular points and interferon metric point, and finally get the trajectory of the end of robots.

Due to the pure effect of description ability of 3D model for the robot of Matlab, in order to show the laser in the manufacturing process of the robot posture intuitively, a laser processing robot Solid Works 3D model is established based on the robot parameters adopted in the Matlab simulation model and is imported into ADAMS. Then the values of 5000 groups of joint Angle which are simulated by Matlab are imported into ADAMS through the import function of ADAMS software as a spline curve. The simulation time of the corresponding joint is 200s, and the simulation animation is obtained by post processing module.

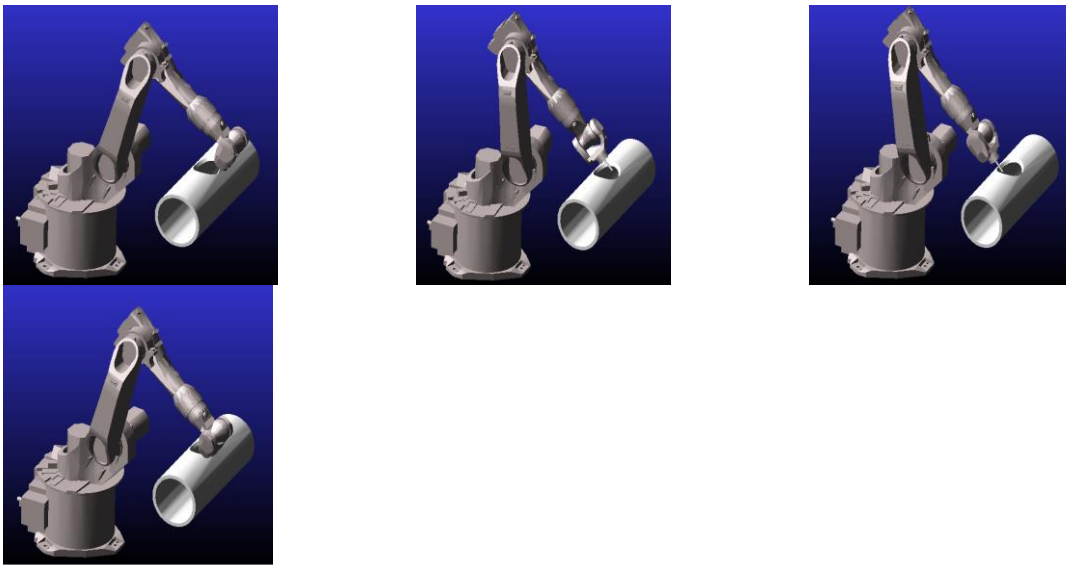

Figure 5. The Simulation Scene Graph

Figure 6 shows the drive torque curve of the each joint of robot obtained from ADAMS. During the cutting process, the robot runs smoothly with no skew phenomenon. The curve is coincided with the torque curve obtained from robot motion simulation. And then verify the reasonableness of the motion simulation of robot after the interference points are excluded.

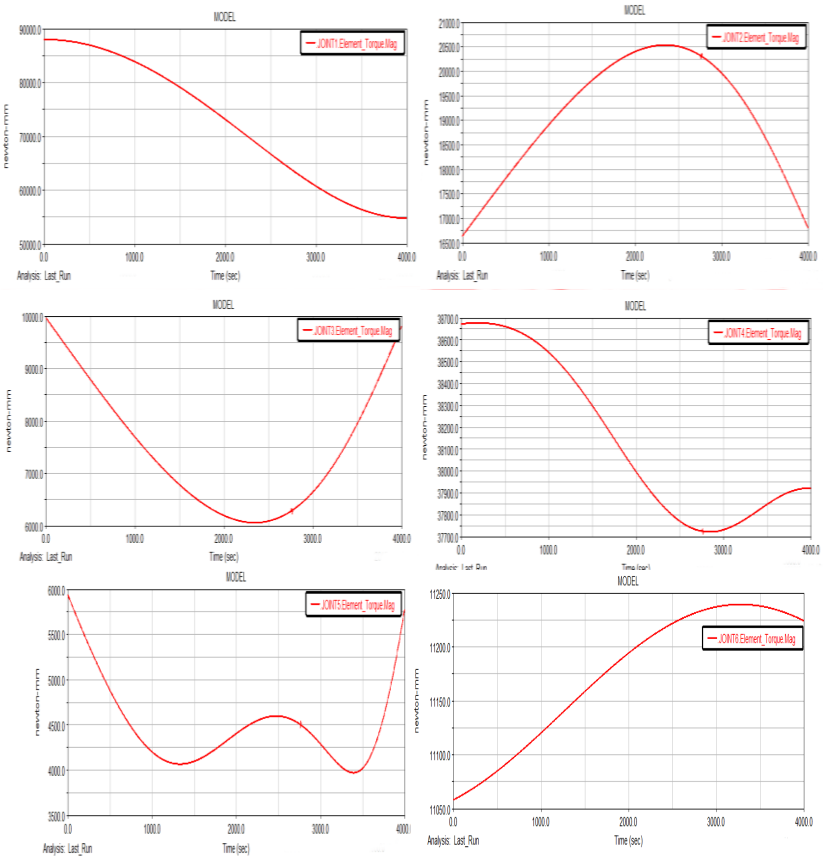

Figure 6. Torque Curves of Each Joint

6. Conclusion

This paper analyses the intersection models and the posture of cutting head, obtaining the intersection model and Euler angles of initial position and terminal position. Programming the cutting trajectory of robot, and with the method of collision detection, which is based on OPENGL, the 3D model of robot, terminal spindle and other parts of equipment are imported into the graphic engine of OpenGL. The posture of robot on the base calibration is turned to the joint angle by inverse transform. The simulation result shows that the robot could run stably in the cutting process after the interference angle is eliminated, and the intersecting line meets the design requirement.

References

[1] J. Zhang, "The new applications of FRP pipe cutting processing", Fiber Reinforced Plastics, vol. 15, no. 9, **(2002)**, pp. 13-20.
[2] Z. Peng, B. You, L.Ding and G. Liu, "Development of Economical NC System for NC Flame Cutting Machine Based on IPC", Journal of Harbin University of Science and Technology, vol. 11, no. 1, **(2006)**, pp. 142-145.
[3] B. Ren, Z. Liang and M. Kong, "An algorithm for the interpolation of circular trajectories of manipulators", Journal of Harbin Institute of Technology, vol. 44, no. 7, **(2012)**, pp. 27-31.
[4] G. Chen, X. Huang and M. Wang, "Trajectory planning for the circular motion of manipulator and its implementation", Journal of Huazhong University of Science and Technology, vol. 33, no. 11, **(2005)**, pp. 63-66.
[5] C. Zeng, C. Zhang and J. Yang, "Trajectory planning of off-line programming of welding line based on Frenet-Serret vector space", Welding Technology, vol. 40, no. 7, **(2011)**, pp. 44-48.
[6] H. Liu and S. Huang, "Robot Continuous Trajectory Planning Based on Freet-Serret Formulas.2010 International Conference on Computer Mechatronic", Control and Elec-tronic Engineering (CMCE) [C] . [s. n.]:[S.1.], **(2010).**
[7] L. Wang, Z. Liu, Z. Li and P. Lin, "Design and kinematics solution of 6-DOF assembly manipulator", Journal of Hebei University of Science and Technology, vol. 35, no. 5, pp. 417-426, **(2014)**.
[8] L. Wang, "The Method of Cutting Trace Control for Intersecting Lines", Mechanical Engineer, vol. 25, no. 2, **(2003)**, pp. 21-23.
[9] J. Cheng and B.You, "Analysis of Planning of KLD-600 Robot Trajectory", Journal of Harbin University of Science and Technology, vol. 15, no. 08, **(2003)**, pp. 30-32.
[10] X. Qiu, X. Yan and S. Feng, "The Implement of Robotic Cutting Trajectory Plan for Pressure Vessel", Applied Mechanics and Materials, vol. 271-272, no. 12, **(2012)**, pp. 570-574.
[11] X. Huang and H. Tian, "Realization of OpenGL for Raged-body Collision Detection Based on Image Space", Computer Knowledge and Technology, vol. 23, no.1, **(2007)**, pp. 439-441.
[12] Y. Song and H. Su, "The collision detection for Rigid-body based on image", Computer Applications and Software, vol. 12, no. 5, **(2004)**, pp. 82-84.

