Tool path generation and back-off error analyze for robot milling process

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Abstract. An improved CC route tool path generation method is presented for robot milling process. Corresponding back-off error model is established based on the robot static elastic model and the ball-end cutter milling force model. Compared with the traditional CC route method, the distance between the adjacent constraint surfaces is adjusted dynamically and thus the milling accuracy will be improved. According to the back-off error model, tool posture can be optimized using genetic algorithms. It is significantly important for reducing the back-off error during robot milling process.

1. Introduction
Milling with industrial robots is becoming more and more popular in the manufacturing field of molds, auto parts and etc. Compared with traditional CNC machining tools, the robot has the advantages of wide working range, small occupied area and excellent flexibility. On the occasions for some light materials that the accuracy request is not very high, industrial robots can replace the traditional CNC machine tools. For example, Niu Xuejuan [1] developed a robotic 3D engraving system. Chen [2] used an industrial robot to mill paraffin, foamed plastic and other materials. Park [3] developed a kind of robot grinding system for large marine propellers.

The application of robot milling processes is restricted by the milling accuracy. The major factors are the back-off error due to the robot joint stiffness and milling forces. In General, the stiffness of industrial robot is weaker than that of CNC machines [4]. It means that industrial robot will cause larger milling error. CAE method [5] and Monte Carlo methods [6] are used to analyze the milling error. However, these methods are usually complex and have difference between the actual situation. Additionally, the perturbation method [7, 8] is used. The robot is treated as flexible rods, and the error compensation is achieved by decoupling method. However, the method cannot give the analyze result in detail.

In this paper, an improved CC route tool path generation method for robot milling process is presented. By adjusting the distance between adjacent constraint surfaces dynamically, the inhomogeneous problem of traditional CC method is avoided. Corresponding back-off error method is then presented based on the static elastic joint stiffness model and the ball-end cutter cutting force model. Simulation and optimization are carried out at last.

2. The improved CC route method for tool path generation
There are several tool path generation methods for free form surfaces: parametric method, guiding surface method and cross-section method. The cross-section method has less amount of calculation. The
control of cutter route is flexible and high efficient and the tool path generated is more uniform. The cross-section method includes CC method and CL method. The CL method is more complex than the CC method, while the CC cross-section method can derive the cutter contact points directly from the intersection of the constraint surfaces and the workpiece surface. The tool path can be generated by offsetting the cutter contact path.

Figure 1. The schematic diagram of CC cross-section method.

The main disadvantage of traditional CC cross-section method is the inhomogeneity problem of the spacing between adjacent intersection curves. In this paper, an improved CC route method is presented. As shown in Figure 2, the problem above is avoided by adjusting the spacing of constraint surfaces dynamically.

Figure 2. Flowchart of the improved CC route method.
In the algorithm, each constraint surface moves with a determined distance $d$ at the beginning, and the cutter contact points can be obtained from the intersection curves. Then calculate the maximum spacing value of two adjacent paths and adjust $d$ if it is out of range.

3. Modelling and optimization of back-off error
The motion of robot is usually not too fast when milling work-pieces and thus can be regarded as quasi-static moving process. The rods of the robot are treated as rigid bodies as their deformation can be ignored compared with the back-off errors.

![Figure 3. Robotic joint stiffness model.](image)

Figure 3 is the robot joint stiffness model reflecting the linear relationship between the joint torque and the rotation angle. Because of the influence of gap, the curve is not continuous at the original point. However, the gap can be ignored as it is usually not too large and thus the robot joint elastic model can be established as follows:

$$\mathbf{\omega} = \mathbf{K}_X \mathbf{\delta}_d = \mathbf{J}^T \mathbf{K}_\theta \mathbf{J}^{-1} \mathbf{\delta}_d$$  \hspace{1cm} (1)

Where $\mathbf{\omega}$ is the twist which is applied to the end of the robot. $\mathbf{K}_X$ is the robot stiffness matrix in the Cartesian coordinate system. $\mathbf{\delta}_d$ is a $6 \times 1$ vector containing the displacement and rotation. $\mathbf{K}_\theta$ is the diagonal stiffness matrix in joint space. $\mathbf{J}$ is the Jacobian matrix of the robot.

In the process of robot milling, the twist $\mathbf{\omega}$ in equation (1) is the reacting cutting force $\mathbf{F}_C$ applied to the cutter. Ball-end cutter is considered in this paper and an empirical model is used to calculate $\mathbf{F}_C$.

![Figure 4. The schematic diagram of ball-end cutter milling.](image)

The ball-end cutter is frequently used for free-form surface milling. As shown in Figure 4, $a_{po}$ is the milling depth. $R$ is the spherical radius of the milling cutter. $h$ is the height of residual areas between milling rows. $h_h$ is the height difference between the cutter tip and the start point of the cutting edge which is involved in cutting. The model of main cutting force is as follows.
When $a_{po} \leq R$ and $h_{b} \leq h$

$$F_{c} = \frac{a_{eo} f_{z} Z p_{2}}{2\pi} \left[\arcsin\left(1 - \frac{h}{R}\right) - \arcsin\left(1 - \frac{a_{po}}{R}\right)\right] + \frac{f_{z} Z p_{1} (h - h_{b})}{\pi}$$ (2)

When $a_{po} \leq R$ and $h_{b} > h$

$$F_{c} = \frac{a_{eo} f_{z} Z p_{2}}{2\pi} \left[\arcsin\left(1 - \frac{h_{b}}{R}\right) - \arcsin\left(1 - \frac{a_{po}}{R}\right)\right]$$ (3)

Where $a_{eo}$ is the milling spacing, $f_{z}$ is the feed engagement. $Z$ is the number of milling teeth. $p_{1}$ and $p_{2}$ are unit cutting forces of different cutting layers.

$$p_{1} = p_{5} \left[\pi / (2 f_{z})\right]$$

$$p_{2} = p_{5} / h_{avp} = p_{5} / \int_{h-a_{po}}^{h} h_{av} / (a_{po} - h) \, dz$$

According to the equations (1), (2) and (3), the milling error $\delta_{F}$ caused by the cutting force $F_{c}$ can be derived as:

$$\delta_{F} = \|K_{X}^{-1} F_{c}\|$$ (4)

The back-off milling error in robot milling process is mainly affected by the cutting force $F_{c}$ and the robot stiffness matrix $K_{X}$. The cutting force $F_{c}$ is mainly depended on the cutting parameters, such as cutting speed $v_{c}$, cutting depth $a_{p}$ and feed rate $f_{z}$, etc. Meanwhile, the robot stiffness matrix $K_{X}$ is determined by the robot joint angles $\theta_{1}$ to $\theta_{6}$. As a result, the back-off milling error of milling process can be reduced and the cutting accuracy will be improved by optimizing the cutting parameters and joint angles.

In this paper, the influence of robot joint angles to the back-off error is studied while the cutting parameters are not considered. Once the cutter contact path is determined, the back-off error is mainly influenced by the posture of the robot which is described by RPY angles ($\theta_{R}$, $\theta_{P}$, $\theta_{Y}$). Genetic algorithm is used here to find the optimal RPY angles. The objective function can be described as:

$$\min \delta_{F}(\theta_{R}, \theta_{P}, \theta_{Y})$$ (5)

4. Simulation and analysis

The following simulation is carried out to analyze the influence of robot postures on back-off milling error. The robot is ABB-IRB140 and the material of the work-piece is magnesium alloy. The parameters used in simulation are as follows:

- Unit of cutting force $p_{5} = 25$MPa;
- $\mu = 0.19$;
- Feed engagement $f_{z} = 0.03$mm/Z;
- Milling spacing $a_{eo} = 3$mm;
- Radius of ball-end cutter $R = 5$mm;
- Cutter tooth number $Z = 2$;
• Robot joint stiffness $k_i = 6 \times 10^5 \text{N/m}, i = 1, 2\ldots6$.

The work-piece is a hemispherical object and its radius is 0.1m. The center point in the robot coordinate system is $(0, 0.7, 0.7)$. Milling error at $P (0, 0.7, 0.8)$ is simulated. $\alpha$ and $\beta$ are the angles between the tool axis and XOZ or YOZ planes. Assume that the available range of $\alpha$ and $\beta$ is $[-1, 1]$. According to the back-off milling error model, the distribution of back-off error is shown in Figure 5.

![Distribution of milling error.](image)

In Figure 5, the minimum value is $6.045 \times 10^{-6}\text{m}$ and the maximum value is $7.064 \times 10^{-5}\text{m}$. The RPY angles of the cutter posture optimized by genetic algorithms are $[0.814, 0.775, -0.862]$. The corresponding milling error is $8.858 \times 10^{-6}\text{m}$ which is close to the minimum value.

5. Conclusion

In this paper, the problems of tool path generation and back-off milling error in robot milling process are discussed. The back-off error model during the milling process is established and the cutter postures optimization method using genetic algorithms is given. Simulation is carried out and shows the feasibility of the optimization to reduce the back-off milling errors.

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