TRAJECTORY OPTIMIZATION AND APPLICATION OF ROBOT IN STAMPING AUTOMATION

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ABSTRACT: To realize the robot instead of manual production, the small and medium-sized stamping enterprises were selected as the object, and the characteristics and requirements of stamping automation production were analysed to improve the production efficiency of stamping. Combined with the theory of robot kinematics and dynamics, the time-based trajectory planning research was carried out under constrained conditions. The trajectory optimization and contrast experiment were carried out on the experimental platform controlled by PLC, and the working efficiency of the robot was analysed. The results showed that by optimizing the motion process of the robot, the efficiency of the robot in stamping production was further improved. In summary, the optimal trajectory planning method based on single cycle is simple and the control effect is good. It has the value of popularization and application in stamping automation production.

KEYWORDS: industrial robot; stamping automation; trajectory planning; time optimization planning; time optimization

1. INTRODUCTION

In recent years, the global manufacturing industry has faced the challenges of transformation and upgrading and sustainable development. There are many reasons for this situation. The aging of labour and traditional production models reduce production efficiency. The structure and situation of the manufacturing industry are constantly changing. Innovation in the field of smart technology is relatively slow in the production environment (Wen et al., 2011). With the concept of "Industry 4.0", the global upsurge in industrial automation has brought hope to the revitalization of the manufacturing industry. The stamping industry is in the basic position of the manufacturing industry, and the demand for automatic production is already impatient. Stamping products are widely used in many industries such as automobiles, machinery, instrumentation, weapons and defence.

Stamping automation is a technology for high-volume or high-efficiency stamping production based on the general stamping process, by improving the feeding mode of stamping production and using automatic stamping equipment and installing various types of automation devices (Thomas et al., 2014). There are also more than 4,000 types of products. With the rapid development of manufacturing, the cycle of product parts replacement is shortened. Traditional production models have been difficult to meet production requirements (Tim et al., 2017). For the majority of small and medium-sized stamping enterprises, the automation level of stamping equipment is backward and the production efficiency is low, which seriously restricts the development of small and medium-sized stamping enterprises (Osakada et al., 2015). Therefore, the production automation of small and medium-sized stamping enterprises is an inevitable trend.

To adapt to the fierce competition of stamping products, stamping companies must keep pace with the times. A new manufacturing mechanism was established, the integration of automation technology and stamping technology was accelerated, and automated stamping production was developed (Sheu et al., 2016). In the process of stamping production automation, automatic loading and unloading and improvement of production efficiency are the main problems. The automatic loading and unloading technologies are relatively mature and has many methods, and it has also been applied in the actual production process. However, there is a slight shortage in flexible production, which is not suitable for the production of multi-variety and small batch stamping parts. For advanced automated stamping lines in foreign markets, small and medium-sized enterprises are difficult to adapt to the market due to their own funds, equipment, sites, technology and other
factors (Lin et al., 2013). With the further development of small and medium-sized stamping enterprises, how to achieve automated production and improve production efficiency based on existing facilities has become a top priority for enterprises. With the development of the stamping industry and the increasing number of manufactured products, how to promote the development of stamping automation to high speed, high precision, flexibility, and full automation has become an important issue for research institutions and production companies (She et al., 2016). To solve the practical problems in the single-machine single-process stamping automation production, the time optimal trajectory planning of the robot was studied. In actual automated stamping production, the results of trajectory optimization are compared and analysed.

Industrial robots are automated equipment that combines multiple disciplines, including mechanical, electrical, computer, and sensor (Robinette et al., 2012). Due to the continuous development of computer technology, Internet technology and MEMS technology, robot technology has been applied in many fields such as industrial manufacturing, home service, entertainment interaction, exploration and detection, disaster relief and rescue (Hu et al., 2015). In the stamping manufacturing industry, the individualized requirements for stamping parts are also increasing. Therefore, flexible production is important for the stamping manufacturing industry. In automated stamping production, industrial robots are mainly used in processes such as demolition and loading and unloading (Lin et al., 2014). With the improvement of robot technology, the advantages of flexibility and high efficiency are obvious. More and more stamping manufacturers are beginning to use the robotic automation system for stamping production. Stamping efficiency and product quality are improved. While achieving significant economic benefits, it is also conducive to the transformation and upgrading of manufacturing (Ning et al., 2012).

In recent years, China has achieved theoretical research results in key technical fields such as presses, fully automatic die change technology and automatic feeding technology. The design and manufacture of the single-machine line stamping automatic production line has been completed, and certain research results have been obtained for the new press. However, in the advanced stamping automation equipment such as large multi-station presses, servo presses and high-speed presses, the research and application techniques are relatively backward. The status quo of China's stamping automation technology has the following characteristics: First, the degree of automation of the stamping equipment is low. For example, large scale multi station presses and advanced automation punching equipment are not widely used. Most of the equipment of small and medium-sized enterprises is generally backward. Loading and unloading is manual. Labor intensity is heavy, energy consumption is high, production efficiency is low, and personnel safety accidents are prone to occur. Second, the efficiency of automation technology is low, and the automation of small and medium-sized enterprises is low. Simple automation equipment is used. The stability is poor and the quality of the parts produced is low. Only part of the stamping production requirements is met. Compared with foreign advanced automatic stamping production lines, the gap is huge. Third, in the manufacture of presses, the performance of foreign presses is advanced. In some processes, the working efficiency is improved from 42 times/min to 100 times/min under the premise of ensuring product quality. The hydraulic press can realize the intelligent mould protection by the operation mode of the hydraulic pressure detecting slider. In contrast, China’s related technologies are relatively backward. The production environment of stamping manufacturing enterprises is generally harsh, the rate of safety accidents is high, and the problem of labour loss is serious.

2. METHODOLOGY

2.1 Demand analysis of robots in single machine single process stamping production

In the enterprise competition, the reduction of the manufacturing cost of products is an important means to enhance the competitiveness of products. It is an effective way to increase production efficiency and reduce costs. Therefore, how to improve production efficiency has always been a key issue in stamping automation research (Zanotto et al., 2013). To improve the efficiency of a single-machine single-process production system, the efficiency of the robot needs to be improved. In a single-process production system, the relationship between the robot and the press, the loading station, and other peripherals is complex. The transmission of signals is frequent. Therefore, the improvement of the robot's motion efficiency is to improve the efficiency of the production of a single-process system. To improve the production efficiency of single-step stamping of a single machine, the robot should meet the following requirements:
First, the robot can work continuously for a long time, and the operation process is stable and safe;
Second, depending on the operating environment, a suitable robot structure is selected. According to the robot and the working process, the optimal motion path is determined;
Third, the speed of the robot must be as fast as possible while satisfying the constraints;
Fourth, the motion law between the robot and the press is reasonably matched to minimize the stamping cycle of the robot and the press.

There are many factors that affect the positioning accuracy of the robot, such as errors in the mechanical structure of the robot, errors in environmental factors, and errors in the system. From the mechanical structure error, the impact on the repeatability of the robot is analysed. The mechanical structure error is mainly divided into the manufacturing error and assembly error of the robot parts. For general industrial robots, their kinematic models are built without regard to errors. However, in actual engineering, there is an error in the dimensional accuracy of the components of the robot during the manufacturing process (Bai et al., 2012). There are also errors in the accuracy of the shape during the assembly of the robot. The above two cases lead to structural parameter errors and joint variable errors, which affect the repeatability of the robot. Since the mechanical structure error of the robot is difficult to avoid, the machining manufacturing precision and assembly precision can be improved within a certain range, and the accuracy of the robot is improved to some extent. In the theoretical study of robots, the characteristics of robot motion are analysed. The precise model of the robot is established by simplifying the processing of the factors that have a great influence on the accuracy of the robot. The model is subjected to kinematics and dynamics analysis, and the trajectory of the robot is planned. Based on theoretical analysis and actual working conditions, the trajectory of the robot is optimized to reduce the influence of error on the repeatability of the robot.

2.2 Stamping robot and its kinematics and dynamics modelling

Figure 1 shows a three-dimensional simplified model of a stamping robot. Table 1 shows the basic parameters of the dimensions and working range of the stamping robot.

![Simplified 3D model of stamping robot](image)

The transmission methods of each joint of the robot are as follows: The joint 1 transmits the rotation of the motor to the ball screw by the timing belt to convert it into a vertical lifting motion. When the ball screw is mounted, the lead screw nut is connected to the link of the joint 1. When the motor drives the lead screw to rotate, the screw nut will move up or down along the axial direction of the lead screw. The spindle nut only moves relative to the earth reference frame without rotation. This avoids the motion coupling effect of other mounting methods of the ball screw. The joint
transmits the rotation of the motor to the input of the harmonic reducer by a timing belt.

Table 1. Basic parameters of the robot

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum profile height / mm</td>
<td>1550</td>
</tr>
<tr>
<td>Working radius / mm</td>
<td>550-1000</td>
</tr>
<tr>
<td>Up and down moving distance / mm</td>
<td>400</td>
</tr>
<tr>
<td>Arm telescopic distance / mm</td>
<td>450</td>
</tr>
<tr>
<td>Boom rotation range / °</td>
<td>-110+110</td>
</tr>
<tr>
<td>End picker rotation range / °</td>
<td>-360+360</td>
</tr>
<tr>
<td>Grab weight / Kg</td>
<td>5</td>
</tr>
</tbody>
</table>

The output of the harmonic reducer is connected to the robot's rotating boom to achieve body rotation (Li et al., 2015). The joint 3 transmits the rotation of the motor to the moving assembly connected to the timing belt by the timing belt. The moving component is connected to the linear guide rail to realize the telescopic linear motion of the robot arm. The motor of the joint 4 is rotated by a planetary reducer and a timing belt drive end picker. The four joints of the robot are driven by an AC servo motor. In the motion of the robot, the limit of each joint movement speed and output force (moment) is calculated according to the parameters of the drive motor and the mechanical structure characteristics of the robot body. Table 2 shows the basic parameters of each joint.

Table 2. Basic parameters of each joint

<table>
<thead>
<tr>
<th>Joint</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor rated power KW</td>
<td>1</td>
<td>0.75</td>
<td>0.75</td>
<td>0.4</td>
</tr>
<tr>
<td>Rated motor speed rpm</td>
<td>2500</td>
<td>2500</td>
<td>2500</td>
<td>3000</td>
</tr>
<tr>
<td>Motor rated torque N.m</td>
<td>4</td>
<td>3.4</td>
<td>3.29</td>
<td>1.27</td>
</tr>
<tr>
<td>Transmission ratio</td>
<td>1:2</td>
<td>1:80</td>
<td>1:3</td>
<td>1:16</td>
</tr>
<tr>
<td>Joint speed limit</td>
<td>0.52m/s</td>
<td>225°/s</td>
<td>3.42m/s</td>
<td>562.5°/s</td>
</tr>
<tr>
<td>Joint drive limit</td>
<td>18890 N</td>
<td>199.1 N.m</td>
<td>219.3 N</td>
<td>43.3 N.m</td>
</tr>
</tbody>
</table>

There are many methods for describing the pose of robots, such as homogeneous transformation method, vector method, spin method and quaternion method. Among them, the homogeneous transformation method is widely used. It combines motion changes with matrix calculations and is also used in researching institutional dynamics and robot motion control.

In the Cartesian coordinate system {A}, the position of any point P can be represented by a 3 x 1 column vector \(^A p\), as in equation (1):

\[ ^A p = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \]  

(1)

\(^A p\) is the positional description of the point P in the coordinate system {A}. \(p_x\), \(p_y\) and \(p_z\) are components of the three coordinate axes of the P point in the coordinate system {A}, respectively.

The orientation of a rigid body P in the coordinate system {A} can be represented by a 3 x 3 matrix \(^A R\):

\[ ^A R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \]  

(2)

\(^A R\) is a rotation matrix. A represents the reference coordinate system {A}, and P represents the self-coordinate system of the rigid body P. \(r_{ij}(i, j=1,2,3)\) represents the elements inside the matrix.

\[ R(x, \theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\theta & -s\theta \\ 0 & s\theta & c\theta \end{bmatrix} \]  

(3)

\[ R(y, \theta) = \begin{bmatrix} c\theta & 0 & s\theta \\ 0 & 1 & 0 \\ -s\theta & 0 & c\theta \end{bmatrix} \]  

(4)

\[ R(z, \theta) = \begin{bmatrix} c\theta & -s\theta & 0 \\ s\theta & c\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \]  

(5)
In the formula, $s\theta = \sin \theta$, and $c\theta = \cos \theta$. They are represented in this simplified form unless otherwise stated.

The position vector is used to describe the position of the point, and the rotation matrix describes the orientation of the rigid body. The pose of an object in the coordinate system is composed of two parts: position and posture. The position vector and the rotation matrix are combined into a fourth-order homogeneous matrix, which is written as:

$$\begin{bmatrix}
1 & 0 & 0 & p_x \\
0 & 1 & 0 & p_y \\
0 & 0 & 1 & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(6)

If the x, y or z axis is used as a rotation transformation with a rotation angle of $\theta$, the rotation matrices are:

$$\frac{\delta}{\delta \theta} T \text{ is a homogeneous transformation matrix.}$$

The mechanical structure between the joints of the tandem structure robot is approximated as a rigid body. The robot is simplified in combination with the actual application environment. The Newton-Eulerian method is used to model the dynamics, which can visually express the joint motion of the tandem structure. At the same time, for the tandem structure robot, the Newton-Eulerian method is more efficient than other methods, which is beneficial to improve the effectiveness of trajectory planning.

The existing pose of the rigid body is compared with the previous pose. The orientation changes and the position remain the same, which is a rotation transformation. In the case where only the rotation transformation occurs, the reference coordinate system of the robot joint changes only the direction of the coordinate axis, and the origin of each coordinate system does not change, as shown in Figure 2. The transformation relationship is as follows:

$$\frac{\delta}{\delta \theta} p = \frac{\delta}{\delta \theta} R \frac{\delta}{\delta \theta} p$$

(7)

Equation (7) is called a coordinate rotation equation or a rotation matrix. $\frac{\delta}{\delta \theta} R$ represents the orientation of the coordinate system $\{B\}$ relative to the coordinate system $\{A\}$.

![Figure 2. Rotation transformation](image)

### 2.3 Trajectory planning of stamping robot based on optimal time

In the production of industrial robots, people are increasingly demanding the efficiency and precision of the robot. The movement mode and trajectory of the robot greatly affect the working performance of the robot. Therefore, the trajectory optimization of the robot is very necessary. The trajectory sought does not represent the optimal trajectory. The constraint is only the position, velocity and acceleration of the first two points, and the shortest time for the motion trajectory is not guaranteed. There are many directions for robot trajectory optimization, such as
optimal system energy, optimal motion path and optimal time. Among them, there are many researches on the optimal time, and the optimization research in this aspect can shorten the working time of the robot and improve the working efficiency.

The joint displacement, joint velocity and joint acceleration equations generated by the previous trajectory planning do not consider the dynamics of the robot. In fact, the acceleration that the robot can achieve is related to factors such as its dynamic performance and the output torque of the drive motor. Moreover, the characteristics of most motors are specified by their torque-speed relationship. Therefore, the optimization algorithm is combined with the robot dynamics. It is an important application direction of robot trajectory planning to transform the problem of improving the working efficiency of robot under constraint conditions into the optimal time of robot. At present, researchers at home and abroad have proposed some research methods in robot trajectory optimization and achieved certain research results. Most of these planning methods are based on multi-body dynamics modelling and optimization algorithms for joint robots. Although the research work has made great progress and breakthroughs in theory, it rarely considers the environmental constraints and working conditions changes in practical applications.

The joints of the robot are driven by servo motors, and the speed and torque of the motor output are limited (Devendra et al., 2014). When the rotational speed and torque constraints of the motor output are converted to the respective joints, the joint speed and the driving force (moment) must satisfy certain constraints. In practical applications, the smaller the value of the exercise time \( t_f \), the better. Therefore, the minimum motion time is taken as the goal of trajectory optimization, and the following mathematical model is established:

\[
\begin{align*}
\text{Goal} & : \min_{t_f} t_f \\
\text{Constraint} & : \\
& \begin{cases}
V_{i_{\text{max}}} \leq \left| \bar{q}_i \right| (t) \leq V_{i_{\text{max}}} \\
\left| \dot{r}_i \right| (t) \leq \tau_{i_{\text{max}}} \\
\left| q_i \right| (t) \leq V_{i_{\text{max}}} \\
\tau_{i_{\text{max}}} \leq \left| \ddot{r}_i \right| (t) \leq \delta
\end{cases}
\end{align*}
\]

For the optimization problem of constraints, the dichotomy can be used to solve the problem. Figure 3 shows the specific steps.
According to the joint variable, the motion time range of the segment trajectory \((t_1, t_2)\), respectively calculate \(t_1 = t_2\), and \(t_1 = t_2\) the maximum of each joint

Drive speed and maximum driving force

If \(t_1 = t_2\), \(t_1 = t_2\), whether the satisfied of constraint condition \((7)\) or \((8)\)

Both \(t_1 \) and \(t_2 \), are satisfied

Take the optimal exercise time \(t_1\), the end of the calculation

Let \(t_3 = (t_1 + t_2) / 2\), when \(t_f = t_3\) calculate the maximum drive and force of each joint

\(t_f = t_3\) is not satisfied, \(t_f = t_2\) is satisfied

Whether \(t_f = t_3\) satisfies the constraint condition \((7)\) or \((8)\)

\(t_f = t_3\)

yes

Take the optimal motion time \(t = t_2\) to end the operation

\(t_1 = t_3\)

no

Figure 3. Flowchart of the dichotomy

Most trajectory planning methods are dynamic modeling and optimization calculations for joint robots. There is very little research on swing arm robots. According to the trajectory planning method, the motion process and state of the robot in the stamping production are analyzed from the actual and application conditions. During the loading and unloading process, changes in load were investigated. At the same time, combined with the performance characteristics of the robot itself, the trajectory of the robot during the loading and unloading movement is optimized as shown in Figure 4.

Figure 4. Hydraulic press and robot
3. REALIZATION OF ROBOT STAMPING AUTOMATION BASED ON PLC CONTROL

Modern industrial automation production gradually connects product information management with production process. As the control center of automatic production, the robot automatic stamping control system needs to integrate the process information of the products in the production process. On the premise of mould protection, process automation is realized, as shown in Figure 5. On this basis, the robot automatic stamping system control framework can be roughly divided into two main aspects: the main control unit and the actuator.

According to the movement trajectory of the joint 1 in the downward reclaiming phase, the servo system position parameter is assigned in the PLC program, and the speed parameter can also be assigned. The program servo driver of the PLC sends a motion command to the servo motor. The motor rotates according to the set position value and speed, and sends a feedback signal to the servo driver through the encoder while rotating. The PLC can perform parameter setting, status reading, register writing and other operations on the servo driver through CAN bus communication. By reading the feedback signal and comparing it with the set information, the running command parameters can be modified in real time to change the motor running position and speed until the joint 1 moves to the set value. Figure 6 shows the control process.
During the operation of the robot, 20 consecutive motion cycles are randomly selected for time statistics. The average of a single cycle is a set of data. A total of three sets of data were obtained. Finally, the average of the three sets of data is solved, which is the time consuming of a single cycle. The time-consuming before and after the trajectory optimization is solved according to the above method, and the three groups of data are obtained. The time consumption of a single cycle before and after optimization is obtained, as shown in Table 3.

<table>
<thead>
<tr>
<th>Table 3. Single cycle comparison of robots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group number</td>
</tr>
<tr>
<td>Before optimization</td>
</tr>
<tr>
<td>After optimization</td>
</tr>
</tbody>
</table>

It can be seen from the data in the table: Before optimization, the single cycle of the robot is 10.71 s. After optimization, the robot's single cycle is 9.33 s. It can be seen from the above experiments that the efficiency of the robot is significantly improved by the optimization method. The actual running time of the robot is longer than the planned time. The main reason is that the period occupied by the hydraulic press to complete the entire blanking process cannot be completely superimposed with the robot running cycle, and the time taken by the logic detecting process during the running of the robot leads to the superposition of the cycle. After one month of actual production statistics, the comparison between manual loading and unloading efficiency and robot loading and unloading efficiency is shown in Table 4. As seen from Table 4, robot loading and unloading is effective in improving production efficiency and labour intensity of workers.

<table>
<thead>
<tr>
<th>Table 4. Comparison of production efficiency of robot loading and unloading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
</tr>
<tr>
<td>Loading and unloading method</td>
</tr>
</tbody>
</table>
4. CONCLUSION

To shorten the working cycle of the automatic loading and unloading process, the time optimal trajectory of the robot is planned. Regarding the development status and future trends of stamping automation, the application of robots in stamping automation is described. The application background and characteristics of single-machine single-process production are analysed. From the three aspects of efficiency, flexibility and precision, the requirements of robots in single-machine single-process production applications are put forward. The parameters of the robot and its characteristics in stamping production were studied, and the working process of the robot in the loading and unloading operation was analysed. The robot is modelled by the linkage coordinate system and the joint transformation matrix is listed. The kinematics and dynamics model of the robot is established by the theory of robot kinematics and dynamics. This lays the foundation for subsequent trajectory planning and optimization calculations. Based on the joint driving force, driving speed and process of engineering, the mathematical model based on time is established by using robot kinematics and dynamics. The dichotomy method is used to optimize the calculation of the shortest exercise time, and the optimal motion trajectory of time is obtained. The trajectory of the robot is simulated by means of software, which proves that the motion law of the robot satisfies the constraint condition.

The dynamics model of the robot is simplified, and some factors such as friction, clearance and deformation between mechanical components are ignored. In some transmission mechanisms of the robot, the frictional force has a great influence on the movement of the joint. Therefore, the dynamics model of the robot is improved. The speed and moment constraints of the motor are introduced when establishing the constraints of the optimized model. However, the torque-speed characteristics of the motor are not considered, so that the motor's motion efficiency is not maximized. The full utilization of motor efficiency should be considered when the time is optimal. Although the automatic loading and unloading movement of the robot can be realized and applied, there are still many details to be improved in actual production. In the future, better solutions should be found to make robots more widely used in stamping automation.

5. REFERENCES


<table>
<thead>
<tr>
<th>Single duty cycle</th>
<th>11.82s</th>
<th>9.33s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single shift yield</td>
<td>2400</td>
<td>300</td>
</tr>
<tr>
<td>Labor intensity of workers</td>
<td>Heavy</td>
<td>Light</td>
</tr>
<tr>
<td>Number of operable machines</td>
<td>1</td>
<td>3-4</td>
</tr>
</tbody>
</table>