Robotic Three-dot Force Feedback to Suppress Surface Contact Slipping in Robot Drilling

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Abstract. Relative to classic machine tools, industrial robots have a low stiffness. In the use of industrial robots during drilling, it is easy to vibrate. When drill bit contacts with workpiece surface, the vibration will cause the drill bit slipping on the workpiece surface, affecting the quality of the drilled hole, so that hole position accuracy can not meet the requirements, which cause the drilling failure. This paper presents a method based on force feedback to suppress the Surface Contact Slipping (SCS). The method using three-dot force sensors to feedback robot’s kinematics, keeps the drill vertical with the workpiece surface, to suppress slipping. Simulation analysis shows that the method can effectively improve the quality of the drilled hole, satisfy the drilling requirements.

Introduction

Large structure processing mainly rely on large-scale NC machine such as aircraft skin assembling, marine sandwich board processing, giant turbine runner repairing and etc. Due to the large volume, high cost, poor flexibility, large CNC machine gradually cannot meet the requirements of market on the production cost and efficiency [1]. In aircraft skin drilling, for example: aircraft assembly processing requires hole position accuracy<0.2mm, diameter error <0.025mm [2], the drilling axial load is usually<400n, the torque load<5N-m. Because of the size of the workpiece and shape error can reach centimeter level, the robot guarantees the position accuracy of holes only though absolute positioning accuracy, rather than repeat positioning accuracy.

In 2002, EI and Boeing company proposed ONCE (One-sided Cell End effectors) drilling robot system [3], in 2011 explained the control system of ONCE and applied ONCE in the Boeing 737 processing [4]. The system uses KUKA KR350 robot as motion platform, and designs a multifunction terminal actuators (MFEE), which is formed by stepping up axis, presser foot, feed axis, and cutting tool and so on. The control system is composed by Fanuc’s CNC and industry PC. ONCE is mainly used for the F/A-18E/F Super Hornet wing trailing edge flaps (TEF), hole locations have successfully been placed within the specification's +/- 0.060" tolerance, countersink depth variation at 0.0025" worst case.

In 2007 Sweden Land university’s Tomas Olsson and etc. basing on IRB2400 ABB robot, designed a very simple terminal actuators, at the end of which is installed three uniformly distributed foots [5]. In the process of making hole, in real time by a six dimensional force sensor to feedback the terminal actuator’s torque and torque to the ABB robot controller, which can restrain the tangential sliding and normal vibration which is relative to the workpiece by the movements of the robots actuators in the process of making hole to guarantee the quality of drilled holes. In 2009 Tomas Olsson improved the terminal actuator which is simpler, lower cost [2]. Current commercial robot using the closed strategy, which cannot be able to process the underlying control link, but Laud University, proposed an open robot controller interface [6], through which we can process the underlying control link of robots.
At home, Beijing University of aeronautics and astronautics [7], in 2010, designed a terminal actuator, which is composed by the pressure unit, spindle unit, feeding unit, presser foot sensor unit and other components, and mainly controlled by PLC, applied for aluminum alloy and titanium alloy. By cutting force feedback to optimize processing parameters such as spindle speed and feed rate, on the 7075-T6 aluminum alloy when the processing hole diameter is 6 mm, the hole diameter size error can be reduced to 0.04 mm, and the surface roughness is between 0.5 ~ 2.0 μm. In 2012, Zhejiang University [8] also designed a hole actuator in the study of aircraft digital assembly system.

Using force sensor can effectively reduce the complexity of terminal actuator, which has substantial advantages for lower manufacturing cost and operational cost. Improvement is presented in this paper based on the research of the Land university experiment system was, with three separate one-dimensional force sensor, rather than a six-dimension force sensor to feedback the robot kinematics. 6 d force sensor is expensive; however, all the forces don’t need to be measured in the feedback. If 6 d force are involved in calculation it will no doubt make the model complex, and have a larger amount of calculation, which will greatly influence real-time feedback. Because three points determine a plane, so you just need to use three force sensors to keep vertical, there is no used four one-dimension force sensors, but use only three one-dimension force sensors.

**Principles of Systems**

**Drilling Vibration Model.** As shown in figure 1, when drilling tool workpiece vibration happens, its vibration model is:

\[
M_r \ddot{x} + C_r \dot{x} + K_r x = F_r
\]

(1)

\[
M_r \ddot{y} + C_r \dot{y} + K_r y = F_y
\]

(2)

\[
M_a \ddot{x} + C_a \dot{x} + K_a x = F_{ax}
\]

(3)

\[
M_a \ddot{y} + C_a \dot{y} + K_a y = F_{ay}
\]

(4)

In the formula, Mr, Cr, Kr, respectively are robot’s mass, frictional damping (x, y orientation), stiffness coefficient(x, y orientation). Ma, Ca, Ka, respectively are terminal actuator’s mass, frictional damping (x, y orientation), stiffness coefficient(x, y orientation). Vibration happens when cutting tool contacts workpiece surface, In the X direction tool point is forced by Fax, robot is forced by Frx; Similarly in the Y direction tool point is forced by Fay, robot is forced by Fry. The four forces causes terminal actuator relative to the spindle axis to produce an α Angle, as shown in figure 2.

![Fig. 1 The model for the horizontal direction vibration](image1)

![Fig. 2 The offset α on point contact with the workpiece surface](image2)

Due to actuators deflection α Angle according to the spindle axis , the end of robot is forced by the horizontal force Frx, Fry and point contacting with the workpiece is under the horizontal force Fax, Fay , which can make robot flange axis force F1, F2, F3 (see figure 4) are not equal.
\[
\begin{bmatrix}
F_1 \\
F_2 \\
F_3 \\
\end{bmatrix} = \begin{bmatrix}
\Delta_1 \\
\Delta_2 \\
\Delta_3 \\
\end{bmatrix} \Lambda (M_r + M_a)(F_r + F_a) \cos \alpha
\]

(5)

In the formula, \(F_1, F_2, F_3\), are forces of different position on robot flange, \(\Delta_1, \Delta_2, \Delta_3\) are Dispersion force coefficient, \(\Lambda\) is vibration coefficient, \(\alpha\) is axis offset Angle, \(F_r\) is robot’s resultant force of \(F_{rx}\) (in the \(X\) direction), \(F_y\) (in the \(Y\) direction), \(F_a\) is tool point’s resultant force of \(F_{rx}\) (in the \(X\) direction), \(F_{ry}\) (in the \(Y\) direction).

When the point contacts with the workpiece surface, the point is forced as shown in figure 3, the deviation occurs, the stress of the blade point are as follows:

\[F_a = \sigma (F_{a1} - F_{a2}) \]

(6)

In the formula, \(F_a\) is tool point’s resultant force of \(F_{rx}\) (in the \(X\) direction), \(F_y\) (in the \(Y\) direction), \(F_{a1}\) is Bounce force of left wall, \(F_{a2}\) is Bounce force of right wall, \(\sigma\) is shear coefficient. When the blade rotation \(\theta\) Angle:

\[F_a = \sigma (F_{a1} - F_{a2}) \cos \theta \]

(7)

In the formula, \(-\pi/2 < \theta < \pi/2\), the cycle \(t=60/n\), \(n\) is speed of spindle). In this simulation \(n=4000\), then \(t=15\) ms.
Control Method. first is through three different position sensor to measure the axial force of robot end flange, and then in real-time feedback robot’s kinematics, the robot adjusts the end position, and always keeps the end of tool perpendicular with the workpiece surface to restrain sliding, as shown in figure 4, the adjustment steps are as follows:

If $F_2$ is not a given value (such as 75 n), then adjust the robot end posture on the z axis displacement until been given.

When $F_2$ adjustment is completed, makes the robot turn around though x axis, until $F_1 = F_3$.

When $F_1 = F_3$, flip around y axis, until $F_1 = F_2 = F_3$.

This is the first round of adjustment, if three forces cannot remain equal, and then adjust again, until three forces always been equal.

Control Process. In robot drilling, flow chart in figure 5 shows how to restrain the tip slipping. Robot feedback is divided into two parts, the first contacting fine-tuning and continued fine-tuning in the drilling process. In the dotted line frame of flow chart is robot feedback process. In the continuous drilling process, if three forces are not equal, then take force feedback fine-tuning.

First boot robot, move the end of robot’s TCP points to teaching point, robot take the first time contact fine-tuning, adjustment process as shown in above steps; Then start the spindle, when the spindle’s speed is given drilling speed, start the feed motor, to drill. In the process of drilling, robot detection whether three forces are equal which are continuously measured by sensors, if they are not equal then take fine-tune, until the end of drilling.

System constitution

The drilling system is mainly consists of the following four parts, which respectively is Industrial IRB4400 Robot, Hole making actuator RDT (Robot - Drilling - test), Force sensor installation disc and Laser Measuring Instrument. Mirror group of Laser Measuring Instrument are installed on the periphery cylindrical of the force sensor installation disc, shown in figure 8.
Industrial robot use ABB’s IRB4400, whose repetitive positioning accuracy is 0.19 mm, payload is 60kg, and maximum working radius is 1.96m. Protection class is IP54, a 6 axis robot, axis1 is rotate C, axis2 is arm B, axis3 is arm A, axis4 is wrist D, axis5 is bent E, axis6 is round P, as shown in figure 6.

Hole making actuators RDt is mainly consists of three parts: one is drilling units, two is linear unit, 3 is to force measuring installation disk. Drilling unit uses Shandong best’s spindle JSZD100 24/3-x, the frequency converter uses 5.5kw JINTIAN JTE200-B, spindle fixed piece uses casting. Feed motor uses Yaskawa servo motor SGMAH-04AAA4, sliding table using Hiwin SBS005-0000, as shown in figure 7.

Robot connection part uses self-made adapting piece. Three force sensors installation disc install on between robot flanges and adapting piece (see figure 8). The force sensors use three one-dimension force sensors ELAF-B0, whose diameter is Φ12.70. On the periphery cylindrical of the force sensor installation disc, there are seven screw mounting holes. First screw the positioning cylindrical rod of mirror group into the screw mounting holes, and then install the lens group on positioning cylindrical rods. Adjust the Laser Measuring Instrument and lens group to measure the displacement and vibration.

Simulation and Analysis

In this paper, the simulation use Solidworks “motion analysis” add-in. First generate two robot virtual walls, set up spring on x and y direction, and then set damping on x and y direction. The parameter settings are in the following table 1:

| Robot  | Tool Point |
|--------|------------|
| Krx (n/mm) | 1463 | Kax (n/mm) | 6 |
| Kry (n/mm) | 1650 | Kay (n/mm) | 8 |
| Crx (n/mm) | 56 | Cax (n/mm) | 1 |
| Cry (n/mm) | 73 | Cay (n/mm) | 2 |
The simulation step is as following:
1. Setup solidworks, enable “solidworks motion” add-in.
2. Configured model as shown in figure 9, setting TCP point and coordinate frame, and the virtual wall which is parallel to the workpiece x, y direction (reference plane).
3. Add gravity, spindle start. Due to this simulation is to test the surface contact slipping, so there is no feed movement. In this simulation spindle rotation speed is 4000r/min.
4. Add spring and damping, and set according to table 2.
5. Calculate simulation and add six measuring scheme, the result is shown in figure 10-15.

**Vibration analysis (Z).** Figure 10 and 11 shows that although use the three-dot force sensors to feedback, the vibration of the z axis has not completely disappeared, but to get a certain suppress and gradually decreases to zero.

![Fig. 10 Without force sensors robot vibration graph of z axis](image)

![Fig. 11 With force sensors robot vibration graph of z axis](image)

**Slipping Suppress Analysis(X).** Figure 12 and 13 shows that although use the three-dot force sensors to feedback, slip suppression on x direction is not obvious. So under the condition that the sliding itself is small, slip suppression is not obvious, but slip did not have increase trend.

![Fig. 12 Without force sensors robot slip graph of x axis](image)

![Fig. 13 With force sensors robot slip graph of x axis](image)

**Slipping Suppress Analysis(Y).** Figure 14 and 15 shows that though use the three-dot force sensors to feedback, slip suppression on y direction is obvious. So force feedback for large slip has fine effect.

![Fig. 14 Without force sensors robot slip graph of y axis](image)

![Fig. 15 With force sensors robot slip graph of y axis](image)

In the two simulation cases, one is with sensors, another without sensors. In the numerical simulation with sensor, add plane collimate spindle end face to workpiece surface, to simulate the effect with sensors. This match is the ideal situation for three force sensors strictly are equal, the specific situation remains to be experimented.

**Summary**

In the process of drilling robot, when cutting tool contact workpiece, vibration will happen. Due to the serial robot has low stiffness relative to machine tool, tool tip will slip when it contact the workpiece surface, which will impact the hole position precision. The surface contact slip may be...
up to 5 mm, but aircraft assembly standard demand hole position error should be less than 0.2 mm, in order to prevent this slipping, this paper proposes a surface contact sliding suppress method based on force feedback.

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