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Design and Implementation of Multifunctional Automatic Drilling End Effector

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Abstract. In order to realize the automatic drilling in aircraft assembly, a drilling end effector is designed by integrating the pressure unit, drilling unit, measurement unit, control system and frame structure. In order to reduce the hole deviation, this paper proposes a vertical normal adjustment program based on 4 laser distance sensors. The actual normal direction of workpiece surface can be calculated through the sensors measurements, and then robot posture is adjusted to realize the hole deviation correction. A base detection method is proposed to detect and locate the hole automatically by using the camera and the reference hole. The experiment results show that the position accuracy of the system is less than 0.3mm, and the normal precision is less than 0.5°. The drilling end effector and robot can greatly improve the efficiency of the aircraft parts and assembly quality, and reduce the product development cycle.

1. Introduction

In the assembly of aircraft structures, all internal and external parts are fixed by solid rivets or fasteners [1]. The quality of holes determines the final quality of the aircraft, manufacturing costs and production cycle. Much of the assembly processes involved in creating high-level structures use conventional manual drilling due to the high complexity of the parts to be processed. Such manual drilling is frequently associated with risk of rework, reduction in the process capability range, and structural impairment, resulting in extra costs [2].

Recently, industrial robotic applications are becoming widely used in the aviation sector [3] because of its lower investment, increasing of automation degree, the table working performance and the good accessibility. From the beginning of twenty-first Century, American GEMCOR, EI (ElectroimPact), Italy COMAU, German BROETJE-Automation is committed to the design and development of drilling robot system, and their drilling robot system production has been used in aircraft manufacturing enterprises, such as F-16, F-22vertical wall, F-35 aircraft wing panel and A380 wing pane [4, 5]. S H Bi developed the drilling robot system, which uses industrial camera to establish the relationship between the workpiece and the robot coordinate system [6].

The end effector is one of the key components of the drilling robot system. The performance of drilling end effector will directly affect the accuracy and efficiency of drilling robot system. In this paper, a drilling end effector is designed to realize automatic drilling of aircraft wing beam, which integrates a variety of function, like as compaction, base detection, vertical normal adjustment, drill and countersink.

2. The structure and principle of drilling end effector

According to the requirements of automatic drilling process for aircraft assembly, the design for automatic drilling end effector actuator includes the following functions: (1) the automatic clamping function; (2) the precision drilling function; (3) high precision countersink function, which can be used for drilling countersink hole of the spindle with the requirements; (4) release and grasp knife function, which can realize the automatic tool changing with the pneumatic actuator and robot; (5) the base detection function, which provide reference measurement data for drilling system; (6) the vertical normal adjustment function, provide deviation data between tool axis and hole position vertical normal for drilling robot system.

Based on the function and space layout, the overall structure of drilling end effector are detailedly designed. The function modules are set as frame structure, pressing unit, drilling unit, robot flange, measurement unit, integrated pneumatic signal unit and integrated electric control unit. The specific structure of drilling end effector is presented in Figure 1.

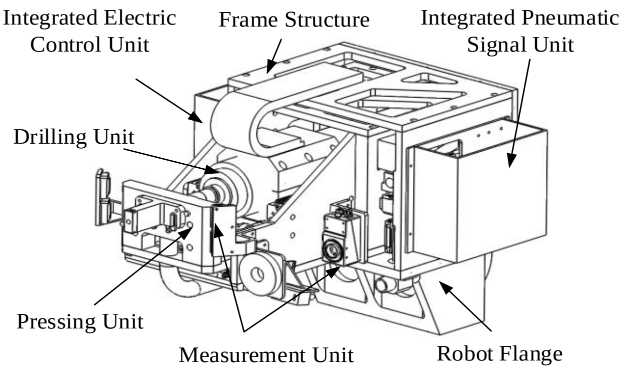


Figure 1. The specific structure of drilling end effector

2.1. Design for Pressing Unit

With standard robotic manipulators, the system provides high degrees of flexibility to enable functionality in large-volume processes, including those involving the manufacture of parts with complex geometries. However, this flexibility causes poor stiffness of the robotic arm, and this relatively lesser rigidity affects the relationship between the end-effector and the work piece, but this low degrees of mechanical stiffness in robotic arms could be compensated by special features fixtures.

The main challenge to be overcome in making increased use of industrial robots in aircraft assembly lines is the positioning accuracy required for these processes. During the entire drilling cycle, the pressure force must be controlled in order to reduce the tangential forces' potential to spoil the hole quality. For instance, the sliding of the drilling tool on the surface during the operation can seriously degrade both the position and other characteristics of the hole.

The whole structure of the pressing unit is shown in Figure 2, which is mainly composed of a pressure nose, a pressure foot, a pair of earrings, a ball bearing, a compression cylinder, a guide rail slide block and a vacuum bypass.

The pressure nose is fixed on the pressure foot, which is connected with the compression cylinder by a pair of earrings and two ball bearings. The ball bearing can be completely connected in a certain processing and assembly error by use the self-aligning function. The pressure foot is connected with the bottom flame plate of the end effector by the high precision guide rail and slide block, and ensures the rigidity of the other direction except the moving direction of pressure foot. The pressure foot end is provided with a chip discharge hole, which is connected with the vacuum bypass.

2.2. Design for Drilling Unit

As shown in Figure 3, the structure of drilling unit includes integrated sliding table, synchronous wheel, servo motor, spindle clamping seat, electric spindle, knife and handle. The servo motor could actuate the integrated sliding table to achieve linear moving by using of synchronous wheel. The feed movement of electric spindle can be realized through the spindle clamping seat and sliding block. The countersink sensor is mounted on the spindle clamping seat and is used for real-time monitoring the depth of drill and countersink.

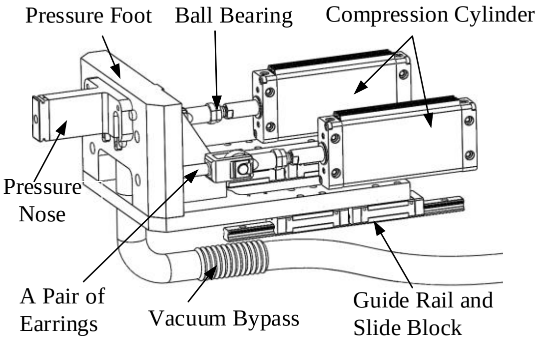


Figure 2. The integral structure of pressing unit

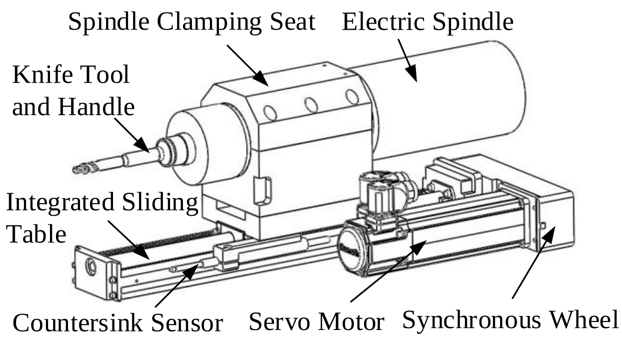


Figure 3. The integral structure of drilling unit

The servo motor is installed on the left side of integrated sliding table, which will makes the drilling unit structure is more compact and reasonable. The actuator power is transferred through the synchronous belt wheel between servo motor and integrated sliding table. The electric spindle rotates knife tool and handle to complete high quality drilling, while the depth of hole and the countersink is critically controlled by countersink sensor which has high measuring precision and response speed. The electric spindle adopts the way of circulating oil to ensure the continuous operation at high speed.

2.3. Principle of measurement unit-- the vertical normal adjustment
The vertical normal adjustment technology is using four laser displacement sensors installed on the drilling end effector to detect and adjust the knife tool posture, which can maintain the deviation between tool axial direction and vertical normal of work piece in a normal range. This technology is one of the key technologies to improve the quality of making hole.

In this paper, the four point vertical adjustment algorithm is used to calculate the intersection angle between tool axis and hole position vertical normal. The measurement principle is shown in Figure 4.

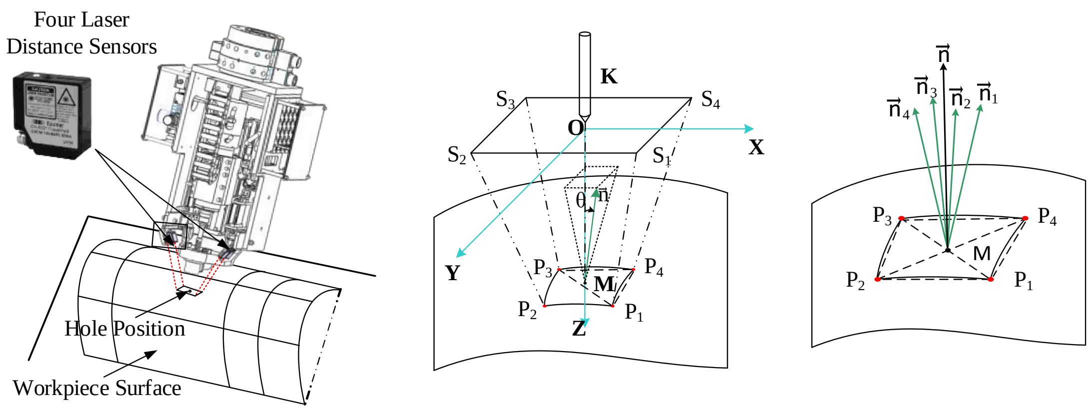


Figure 4. Principle diagram of vertical normal adjustment in Drilling end effector

Four laser distance sensors is installed on the both sides of drilling end effector, and the projection direction of the laser distance sensor and the actual position in reference coordinate system are already calibrated as premise work [7]. In Figure 4, the position of four laser distance sensors are respectively presented S_1, S_2, S_3 and S_4. P_1, P_2, P_3 and P_4 are the light spots on the surface of workpiece emitted by the laser beam of four laser displacement sensors. Before the drilling-hole process, four laser distance sensors are used to measure the distance the light spots and sensors. By using the distance data of four sensors, the coordinate value of P_1, P_2, P_3 and P_4 in O-XYZ coordinate system can be calculated respectively. Since any three points of P_1, P_2, P_3 and P_4 are not collinear, four points can be formed around four micro processing plane ($P_1P_2P_3$, $P_1P_2P_4$, $P_1P_3P_4$ and $P_2P_3P_4$). Four normal vectors ($\vec{n}_1$, $\vec{n}_2$, $\vec{n}_3$ and $\vec{n}_4$) of four micro plane can be deduced with normal calculation mathematical model and coordinate value of three point. By using the specific algorithm, four normal vectors are "weighted average" to approach the actual normal vector of the machining point M.

In the vertical normal adjustment process, the measured data of laser distance sensors are assumed to be l_1, l_2, l_3 and l_4. Then, the coordinate value (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3) and (x_4, y_4, z_4) of P_1, P_2, P_3 and P_4 in O-XYZ coordinate system can be written as:

$$\begin{cases} x_i = (l_i - l_i^0)\cos\alpha_i \cos\beta_i + \triangle x_i^0 \\ y_i = (l_i - l_i^0)\cos\alpha_i \sin\beta_i + \triangle y_i^0 \\ z_i = (l_i - l_i^0)\sin\alpha_i \end{cases} \quad i=1, 2, 3, 4 \tag{1}$$

Where l_i are the measured data of laser distance sensors, l_i^0, $\triangle x_i^0$ and $\triangle y_i^0$ are the constant value, which are determined in premise calibration procedure. α_i are angles between the laser beam direction of four laser distance sensors and the reference plane of the tool coordinate system. β_i are angles between the projection line of the laser beam on the reference plane and the Coordinate axes Y. α_i and β_i are already deduced in premise calibration procedure, too.

In each micro plane of $P_1P_2P_3$, $P_1P_2P_4$, $P_1P_3P_4$ and $P_2P_3P_4$, the normal vector two of micro plane can be cross multiplied with two vectors composed by three points:

$$\overrightarrow{n_1} = \frac{\overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3}}{\left|\overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3}\right|},\ \overrightarrow{n_2} = \frac{\overrightarrow{P_1P_2} \times \overrightarrow{P_1P_4}}{\left|\overrightarrow{P_1P_2} \times \overrightarrow{P_1P_4}\right|},\ \overrightarrow{n_3} = \frac{\overrightarrow{P_1P_3} \times \overrightarrow{P_1P_4}}{\left|\overrightarrow{P_1P_3} \times \overrightarrow{P_1P_4}\right|},\ \overrightarrow{n_4} = \frac{\overrightarrow{P_2P_3} \times \overrightarrow{P_2P_4}}{\left|\overrightarrow{P_2P_3} \times \overrightarrow{P_2P_4}\right|} \tag{2}$$

The weighted average of four normal vector is obtained as the actual normal vector of the machining point M:

$$\vec{n} = \frac{1}{4}(\overrightarrow{n_1} + \overrightarrow{n_2} + \overrightarrow{n_3} + \overrightarrow{n_4}) \tag{3}$$

Then the angle θ between the tool axial direction and actual normal vector $\vec{n}$ is:

$$\theta = arc\cos([1\ \ 0\ \ 0] \cdot n) = arc\cos(n(1,1)) \tag{4}$$

If $\theta < 0.5^{\circ}$, then there is no need to implement the vertical normal adjustment program. If $\theta \geq 0.5^{\circ}$, the vertical normal adjustment diagram will be steadily carried out until meeting the requirements.

2.4. Principle of measurement unit-- the base detection

In the drilling process, the position of drilling holes is located with a high precision industrial camera to identify the reference hole on the workpiece. When the robot arrive at the designated location, there is a deviation between theoretical robot coordinate system and the actual robot coordinate system. On the otherwise, the installation of processing parts may also produce deviation the workpiece and the theory position, as shown in Figure 5.

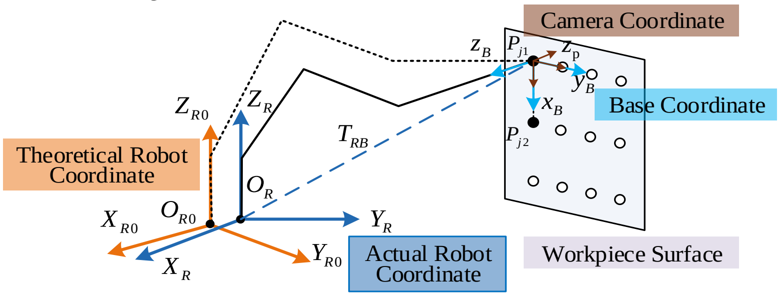


Figure 5. Principle diagram of base detection in Drilling end effector

These reasons will lead that the actual position relationship between the robot and processing parts is different with the theoretical relationship. Therefore, the base detection program is necessarily implemented to establish the base coordinate system and determine the actual position between parts workpiece and drilling end effector.

The original point of camera coordinate system is define as $POS_{Rp}(x, y, z, A, B, C)$. (x, y, z) means the coordinate value of POS_{Rp} in actual robot coordinate system, while A, B, C are the angles of Euler transform from the base coordinate system $O_R - X_R Y_R Z_R$ to the camera coordinate system $P_{j1} - x_p y_p z_p$. Then, the homogeneous matrix of Euler transform can be written as:

$$T_{Rp} = Trans(x, y, z) \bullet Rot(z, A) \bullet Rot(y, B) \bullet Rot(x, C)$$
$$= \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} \cos A & -\sin A & 0 & 0 \\ \sin A & \cos A & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} \cos B & 0 & \sin B & 0 \\ 0 & 1 & 0 & 0 \\ -\sin B & 0 & \cos B & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos C & -\sin C & 0 \\ 0 & \sin C & \cos C & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$
$$= \begin{bmatrix} \cos A \cos B & \cos A \sin B \sin C - \sin A \cos C & \cos A \sin B \cos C + \sin A \sin C & x \\ \sin A \cos B & \sin A \sin B \sin C + \cos A \cos C & \sin A \sin B \cos C - \cos A \sin C & y \\ -\sin B & \cos B \sin C & \cos B \cos C & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Two base holes are pre-made before the base detection, then the drilling end effector is approach to base hole P_{j1} by operating the robot arm and made the circle center of hole P_{j1} into the camera vision center. At this moment, the base detection program will record point coordinates value P_{pj1} of P_{j1} in the camera coordinate system $x_p y_p z_p$. According to the same process, point coordinates value P_{pj2} of P_{j2} in the camera coordinate system $x_p y_p z_p$ will be accurately identified. The base coordinate system $x_B y_B z_B$ will be established on the basis of P_{pj1} , P_{pj2} and T_{Rp} .

3. The experiment research

In this experiment, we have developed a Drilling End Effector system which is installed on Kuka KR-500 robot as the experiment platform, as shown in Figure 6.

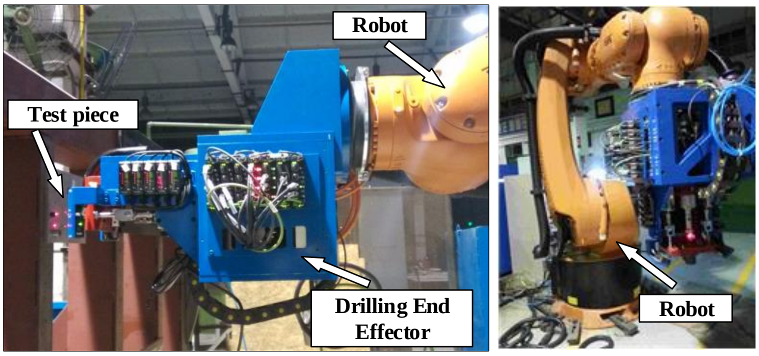


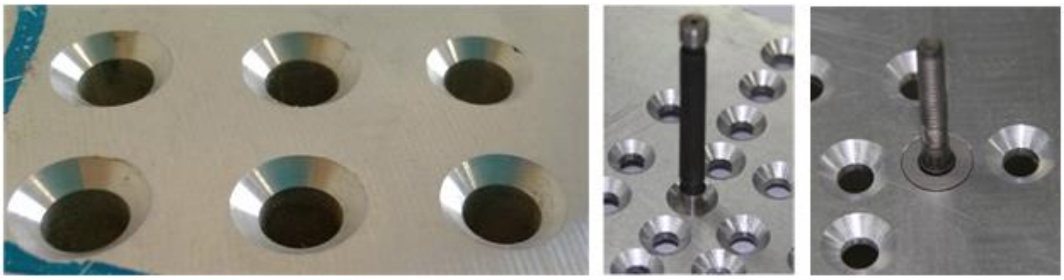
Figure 6. The experiment platform of Drilling end effector

The measurements and calculation results of vertical normal adjustment program are shown in table 1, the angle error shows that the method to meet the accuracy requirements (less than 0.5 deg).

The robot and drilling end effector can realize auto-drilling for Aluminium laminated material, and the efficiency can reach 6 holes / min. The parameters of holes can meet the drilling requirements, which greatly improve the drilling efficiency and quality of aircraft components assembly. The results of drilling hole experiment and precision measurement are shown in Figure 7. The position error of holes is less than 0.3mm; the diameter precision can reach H9; the vector normal errors of all the holes are less than 0.5°, and the holes' surface roughness is less than 1.6 μm.

Table 1. The results of vertical normal adjustment program

Num.	Laser senor 1	Laser senor 2	Laser senor 3	Laser senor 4	Calculated angle (Deg.)	Actual Value (Deg.)	Error (Deg.)
1	135.90	138.60	136.50	134.30	0.106	0.063	0.044
2	144.23	146.93	144.83	142.63	0.086	0.062	0.025
3	144.07	146.77	144.67	142.47	0.098	0.073	0.025
4	135.74	138.44	136.34	134.14	0.112	0.103	0.009
5	139.74	142.44	140.34	138.14	0.050	0.063	0.112
6	135.64	138.34	136.24	134.04	0.097	0.061	0.036



(a) (b) (c)

Figure 7. The experiment and precision measurement: (a) countersink specimens; (b) diameter detection; (c) countersink depth detection

4. Conclusion

A drilling end effector is designed for the robot automatic drilling system. Through the research of pressing unit, drilling unit and measurement unit, the effective integration of each functional module of drilling end effector is realized. The vertical normal adjustment is proposed to significantly improve the vertical accuracy of the robot automatic drilling system and the base detection program can be realize the automatic orientation of base coordinate system. The experiment research illustrate that drilling end effector and robot can greatly improve the efficiency of the aircraft parts and assembly quality, and reduce the product development cycle.

5. References

[1] Webb, P., N. Jayaweera and G. Lowe 2007 *Assembly Automation* **27**(4) 343
[2] Bo Yong, X.G.-k. and Xiao Qing-dong 2009 *Aeronautical Manufacturing Technology* **24** 61
[3] Olabi A, Béarée R, Gibaru O and Damak M 2010 *Control Engineering Practice* **18**(5) 471
[4] Atkinson J , Hartmann J and Jones S P 2007 SAE AeroTech Congress & Exhibition (Los Angeles, CA, USA) 28
[5] DeVlieg R, Feikert E, One-up assembly with robots[J]. Training, 2008. **2013**: p. 09-30.
[6] Bi S S, and Liang J 2011 *The International Journal of Advanced Manufacturing Technology*,. **54**(5) 767.
[7] Wang Z C, Qin X S, Bai J and Wang W L *Machinery Design & Manufacture* 2014 **6** 160.

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