Precision Engineering xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Research on surface normal measurement and adjustment in aircraft assembly

Long Yu, Yilian Zhang, Qingzhen Bi, Yuhan Wang*

State Key Laboratory Mechanical System and Vibration, School of Mechanical engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

ARTICLE INFO

Article history:
Received 26 January 2017
Received in revised form 28 May 2017
Accepted 6 July 2017
Available online xxx

Keywords:
Aircraft assembly
Normal measurement
Adjustment
Drilling and riveting
Kinematic model
Bracket length measurement

ABSTRACT

Drilling and riveting are commonly used in aircraft panel assembly process. Due to the fixture positioning error and the deformation of workpiece, the real position and orientation of the workpiece as well as its 3D geometry at the drilling position varies from the nominal CAD model, which would cause an unfavorable impact on assembly quality. Therefore, surface normal measurement and adjustment at the drilling position is of great importance. In this paper, a fast and effective non-contact measurement method for normal vector and height of moderately curved surfaces is accomplished by four laser displacement sensors, and a dedicated NC machine tool is also developed for normal adjustment. Firstly, a novel sensor calibration method based on laser tracker is introduced, which can acquire the sensors' position and orientation in Tool Coordinate System (TCS) at the same time. The normal vector at hole position is calculated by cross product of any two non-parallel vectors constructed by the four laser projection points on the panel surface. Secondly, the kinematic model of the machine tool is established to calculate the adjustment of each axis of the machine tool with the Homogeneous Transformation Matrix (HTM). Besides, an innovative method to identify the distance of two rotary centers based on two laser interferometers is proposed. Finally, a series of experiments are conducted to validate the feasibility of the proposed method. The results show that the angle deviation can be reduced to less than 0.5° after adjustment, while the accuracy of the surface height is ±0.04 mm.

1. Introduction

Automated drilling and riveting systems are playing predominant roles in aircraft assembly with increasing needs for higher productivity and more reliability [1,2]. The quality of the riveting directly impacts the performance and safety of the aircraft, which significantly depends on the precision of the riveting hole, especially its verticality [3]. The experiment on Ti alloy indicates that the fatigue life of the bolt will reduce 47% if the riveting holes tilt beyond 2° [4]. Therefore, to meet the requirement of automated fastening on surface panel, an automated drilling and riveting system with the function of normal measurement and adjustment is necessary.

Researchers have developed a variety of surface normal measurement methods and algorithms. Among them noncontact laser sensors are commonly used. Using three laser sensors distributed around the drill bit to measure the angle deviation of the pressure plate, Lin et al. [5] proposed a novel surface normal measurement method for autonomous drilling robot system, This method is effective for flat and moderately curved surfaces. However, for a highly curved surface, there is not enough contact area between the pressure plate and the part. Tian et al. [6] employed four noncontact laser displacement for surface normal measurement in robotic drilling system, these sensors are installed in a cruciform structure, and the four laser beams of the sensors distributed on a virtual conic surface. This method is easier and faster but has relatively low accuracy. Moreover, the mounting space of the sensors is limited, and its measurement precision is difficult to quantitatively analyze during the design phase. Based on the advanced mathematics and geometry, Gao et al. [7] presented an algorithm for calculating the measurement precision of the new approach to arrange the four displacement sensors in a rhombus layout. This algorithm makes it possible to predict the performance of the normal measurement during the design phase. Zhang et al. [8] applied two 2D laser displacement sensors to measure the surface normal of the deformed workpiece. Two sets of geometrical points can be sampled by the sensors each time, and then two crossed spatial curves can be fitted to compute the surface normal at the intersection point of the crossed curves. It has been validated by experiment that this method can achieve high accuracy normal measurement. However,

---

* Corresponding author.
E-mail address: yuhan_wang0309@163.com (Y. Wang).

http://dx.doi.org/10.1016/j.precisioneng.2017.07.004
0141-6359/

Please cite this article in press as: Yu L, et al. Research on surface normal measurement and adjustment in aircraft assembly. Precis Eng (2017), http://dx.doi.org/10.1016/j.precisioneng.2017.07.004

the 2D laser displacement sensors are too big to be integrated on the end-effector, and this kind of sensor will increase the cost.

Besides laser displacement sensor, 3D laser scanner is also widely utilized to obtain the actual surface normal [9,10]. OuYang and Feng [11] found that the reliable surface normal determination based on laser scanning data set was essential to CAD model construction. Calderon [12] put forward an algorithm for surface normal determination using a neighborhood strategy based on local piecewise planes, and this algorithm greatly improved the accuracy of surface normal determination. The surface normal measurement based on 3D scanner is a promising method, but it is time-consuming compared to laser displacement sensor as the point cloud data is needed to process in 3D scanner technology, while only four points are used to calculate the normal in laser displacement sensor, which is easier and faster but relatively low precision [13]. In detail, the 3D scanning process is usually implemented by a 2D laser displacement sensor combined with a translational motion [14]. Therefore, scanning at low speed can generate high resolution data set but it is not efficient, while scanning at high speed could cause a low resolution problem that may misrepresent a surface [9].

Furthermore, a laser projector together with two CCD cameras has also been applied to measure the normal vector of an unknown 3D surface [15]. Two curves will be generated when the laser cross is projected on the surface by the projector, which can be gathered by the two fixed cameras. Consequently, the two curves can be reconstructed by the image processing. Afterward, the normal vector at the laser cross center can be calculated based on the geometrical methods. This method is suitable for complex surfaces measurements, but it is difficult to integrate into the drilling and riveting system because of the limited installation space. Besides, the measurement accuracy is limited by the image resolution of the CCD cameras, and a high accuracy calibration method is needed.

Since non-contact measurements are susceptible to loss of accuracy due to cutting debris, Sean Holt and Rider Clauss of Electroimpact [16] have developed a novel measurement method based on contact sensors to achieve accurate drilling and countersinking holes on highly convex parts. They developed a pneumatically actuated four-point lander on a compliant contact pad with normality feedback, and along with the accurate robot technology, this development allows for automated drilling and countersinking on parts that have previously been unachievable with robotic drilling system. This method can deal with highly curved surface and maintain accuracy, but it's difficult to implement as the device is complex and has high integration demands.

After normal measurement, the tool axis should be adjusted to be coincident with the measured normal of the current surface. Yuan et al. [17] designed a novel adjusting mechanism composing of two eccentric discs and a spherical pair, which can keep drill vertex immobile in normal adjustment process. Iovenitti et al. [18] developed a vector setting device to align the axis of the drill bushed with the arbitrary desired vector. In addition, articulated arm robots are commonly used in normal adjustment due to its low cost and high flexibility [16]. What's more, Eastwood et al. [19] developed the TI^2 manufacturing system which based around a parallel manipulator named as NEOS Tricept® robot and a photogrammetric measurement system, which can orient the end-effector to the part without the need for precise and costly physical location systems. However, Aircraft automated drilling and riveting systems usually involve clamping, drilling, countersinking, injecting sealant, rivet feeding, and riveting [20]. Due to the limits of weight and dimension, the end-effector integrating with all these functions is inflexible for posture alignment.

Using a dedicated gantry machine tool, this paper proposes a fast and effective method of normal measurement and adjustment for flexible panel parts with small curvature, especially the single curved surface, such as the aircraft fuselage. To be emphasized, the height from the nosepiece of clamping foot to the drilling point of the surface is measured synchronously with the normal measurement, which can guarantee the countersink depth. Meanwhile, the posture of the workpiece is adjusted by the numerical control (NC) compensation while the height can be synchronously adjusted to the prescribed value. In Sect. 2, the principle of normal sensor calibration is described. In Sect. 3, the normal vector is calculated by the cross product of any two vectors constructed by the projection point on panel surface. In Sect. 4, the method of normal adjustment with NC compensation is proposed, including kinematic model development, bracket length measurement and the normal adjustment process. In Sect. 5, a series experiments are carried out to validate the method, and the contributions of the proposed method are summarized in Sec. 6.

2. Normal sensor calibration

Laser distance sensors are commonly used to achieve non-contact accurate distance measurements, which have many advantages such as wide application range, low requirement on the measured part, high reliability and security [21]. However, it is not without its shortcomings, especially the difficulty to locate its zero point and orientation. In order to locate the space position and the direction of the laser emission, laser distance sensors are calibrated by the laser tracker. And in normal measurement, four laser sensors are frequently adopted to increase the fault tolerance. As shown in Fig. 1, S_1–S_4 represent the laser distance sensors, while the red dotted lines represent the direction of the laser beams. $S_1^{'} - S_4^{'}$ are the four laser projection points on the datum plane. The sensors can be calibrated through several different datum planes.

Denoting the position of the 4 laser displacement sensors in TCS as $\boldsymbol{P}(i)(x_i, y_i, z_i)(i = 1 \cdots 4)$, the laser emission directions as $\boldsymbol{O}(i)(m_i, n_i, p_i)(i = 1 \cdots 4)$, and the distance between sensor's origin and datum plane as $l_i(i = 1 \cdots 4)$.

Accordingly, the coordinates of the projection points of laser beams on datum plane $\boldsymbol{P}'(i)(i = 1 \cdots 4)$ are

$$P'(i) = P(i) + l(i)O(i) = \begin{pmatrix} x_i + l_i \cdot m_i \\ y_i + l_i \cdot n_i \\ z_i + l_i \cdot p_i \end{pmatrix} \tag{2.1}$$

The datum plane can be defined by

$$ax + by + cz = d \tag{2.2}$$

where a–c are the three components of unit normal vector of the datum plane, that is,

$$a^2 + b^2 + c^2 = 1 \tag{2.3}$$

Denoting d as the distance from origin of TCS to the datum plane, and $d \geq 0$. The projection points are on the datum plane satisfying Eq. (2.2), then

$$a(x_i + l_i \cdot m_i) + b(y_i + l_i \cdot n_i) + c(z_i + l_i \cdot p_i) = d \tag{2.4}$$

To determine the position and orientation of each sensor, six non-parallel datum planes are needed, which are expressed as

$$\begin{cases} a_1(x_i + l_{1i}m_i) + b_1(y_i + l_{1i}n_i) + c_1(z_i + l_{1i}p_i) = d_1 \\ a_2(x_i + l_{2i}m_i) + b_2(y_i + l_i n_i) + c_2(z_i + l_{2i}p_i) = d_2 \\ a_3(x_i + l_{3i}m_i) + b_3(y_i + l_{3i}n_i) + c_3(z_i + l_{3i}p_i) = d_3 \\ a_4(x_i + l_{4i}m_i) + b_4(y_i + l_{4i}n_i) + c_4(z_i + l_{4i}p_i) = d_4 \\ a_5(x_i + l_{5i}m_i) + b_5(y_i + l_{5i}n_i) + c_5(z_i + l_{5i}p_i) = d_5 \\ a_6(x_i + l_{6i}m_i) + b_6(y_i + l_{6i}n_i) + c_6(z_i + l_{6i}p_i) = d_6 \end{cases} \tag{2.5}$$

Please cite this article in press as: Yu L, et al. Research on surface normal measurement and adjustment in aircraft assembly. Precis Eng (2017), http://dx.doi.org/10.1016/j.precisioneng.2017.07.004