Research on measurement path planning of complex object

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Abstract. In the past automatic measurement system for three-dimensional shape of complex parts, there was no corresponding measurement scheme for the groove-shaped complex parts, which there existed problems such as low work efficiency and large measurement error. In order to solve this problem, this paper is based on the principle of raster scanning projection measurement, and explores the mathematical model of projection grating trigonometry theory, and analyzes the different characteristics of scattered geometric features such as walls and edges inside the groove in complex parts. Combined with the scanning constraints such as the inclination angle and depth of field of the 3D scanner, the method of measuring the path planning of the groove-shaped complex parts was proposed and studied. Finally, the measurement path planning verification experiment was carried out, which is based on the above analysis. The results show that the position deviation during the measurement process is within 0.001mm, the angular deviation is within 0.009°, which proves the feasibility of the measurement path for the groove-shaped complex parts.

1. Introduction

Three-dimensional measurement technology has received wide attention around the world in recent decades. This technology has been applied in many fields, especially in aerospace and automotive manufacturing. It can measure the three-dimensional shape of many kinds of objects, which can be applied in the reverse engineering, virtual assembly and etc. Therefore, better measurement of the three-dimensional shape of the measured object and improvement of measurement efficiency become one of the problems of the current research. Nowadays, the methods to realize three-dimensional measurement can be roughly classified into contact measurement and optical non-contact measurement [1-3].

Many scholars have conducted related research on 3D measurement or methods to improve measurement accuracy. The joint measuring arm introduced by FARO in the United States was mainly designed, which can realize the contact measurement of the points to be measured at different positions in space [4]. An arm of an articulated three-dimensional measuring appliance can allow measurement correction by comparing with constant force [5]. In 2010, Zhang, et al. combined optical scanners and three coordinate measuring machine to improve the accuracy of mold edge measurement, and the processing quality was guaranteed [6]. Although the measuring arm and CMM have extremely high measurement accuracy and stability and can be used for off-line arranging, the measurement method is mainly static and the measurement efficiency is low. Besides, this measurement equipment mainly used contact measurement method, which would affect the parts with high surface characteristics.
A new concept for 3D shape measurement of complex objects was proposed, which is based on photogrammetry and fringe projection. Carsten Reich, et al. proposed a new concept for shape measurement of complex objects, which was based on combining photogrammetry and fringe projection. Partial views of the object shape were acquired by a passive fringe projection sensor consisting of a projector and two cameras. According to acquiring the point clouds taken from different sensor positions can be transformed into the global coordinate system with very high precision. This technology could achieve three-dimensional shape measurement of objects [7]. Although this measurement technique had been widely used, the above measurement methods did not achieve good topography measurement for parts or objects with complex shapes. At the same time, a single and fixed measurement path can not meet a variety of object types and could affect measurement efficiency.

Considering the current problems, in this paper, we proposed a new measurement path method of groove-shaped complex parts. Optical non-contact measurement technology using raster scanning solves the influence of contact measurement on the surface of the part, and the measurement effect is better. Plan a measurement path for the groove-shaped part, which can well realize the topography measurement of this type of part and improve the measurement efficiency. Finally, the experimental results prove that this study is feasible.

2. Theoretical analysis

2.1. Principle of projection grating

The projection grating method is a kind of active full-field triangulation technique. The basic idea of the projection grating method is to project the structured light to the object and observe it in a direction different from the projection optical axis. Measure the three-dimensional appearance of an object by using the triangular relationship among the target object, the projection point, and the observation point (the trigonometry method). The scanner projection lens projects different stripe patterns onto the object being measured, also, the scanner uses two cameras to observe their trajectories. The system performs Fourier analysis, threshold filtering and inverse Fourier transform on the images acquired by the two CCD cameras, and the processing unit automatically and accurately calculates the 3D coordinates of each pixel of the camera. According to the camera resolution as the effect of this scan, we obtain up to millions of point clouds per measurement, and the measurement principle is shown in Figure 1.
In the picture, CCD represents two cameras attached to the scanner, which are used to observe their trajectories and process the captured image. P, P1, and P2 represent some point on the surface of the object to be tested and the imaging points in two cameras respectively.

2.2. Projection grating triangulation theory mathematical model

When the grating is projected onto the surface of the object, the optical geometry of the system is shown in Figure 2. In the picture, the projection lens of the exit hole and the photographic lens of the entrance hole are denoted by points A and B respectively. Then the position of the optical sensor is determined by the reference line b and the distance a. The coordinate system of the plane of the projection lens and the coordinate system of the photographic lens plane are \((X_A, Y_A, Z_A)\) and \((X_B, Y_B, Z_B)\) respectively, whose the origins are point A and point B. Besides, the axes \(Z_A\) and \(Z_B\) and the optical axes of the projection lens and the photographic lens are respectively coincident. The height information is defined as the height along the Z coordinate axis in the reference coordinate system \((X, Y, Z)\). PS and PT are the two edges of the projection that are projected by the projection lens and can be captured by the camera. These two rays also determine the length of the visual range FW along the X-axis. \(Q\) is a point on the surface of the object, the angle between the \(A\) \(Z\) axis and AQ is \(\phi\). The length \(QQ'\) is the height of the point Q. When the light emitted from the projector AD can be seen from the camera lens DB without object placed, conversely, if the object is placed, the PB will be seen from the camera AD.

![Figure 2. System optical structure geometry.](image)

From the above analysis, according to the basic relationship of the trigonometry, the height information of the point Q can be obtained:

\[
h(x, y) = a \cdot \frac{PD}{PD + b}
\]  

(1)

In the vicinity of the optical axis, the imaging system can be viewed as linear and translational. Based on this assumption, a three-dimensional spatial coordinate system and a two-dimensional observation coordinate system of the space can be established as shown in Figure 3.

Among them, the three-dimensional space coordinate system \((X, Y, Z)\) represents the spatial position of the whole system, which is the coordinate system of the measured object, and the two-dimensional observation coordinate system \((x, y)\) is used to represent the imaging plane of the camera. Assume that the target object to be measured is placed at the origin of the space coordinate system.
origin \(O(0,0,0)\), the projection lens focus is at point \(A(0,0,a)\) (in the three-dimensional space coordinate system), the camera lens focus is at point \(B(0,b,a)\) (in the three-dimensional space coordinate system). Also, the imaging point of the origin \(O\) of the spatial coordinate system on the imaging plane of the camera is \(o(0,b+d,a+c)\) (in the three-dimensional space coordinate system), and the point \(o(0,b+d,a+c)\) is the origin of the two-dimensional observation coordinate system. When the angle \(\Phi_n\) between the line \(AN\) of the projection stripe and the plane \(XOZ\) is set, the coordinate of the point \(D\) on the stripe projected onto the plane \(XOY\) is \((X,a \tan \Phi_n,0)\). Suppose a point \(Q\) is on a space object, its coordinate in the three-dimensional space coordinate system \((X,Y,Z)\) is \(Q(X_Q,Y_Q,Z_Q)\), and its image in the imaging plane corresponds to the coordinate \(q(x_q,y_q)\).

2.3. Scanning Constraints

The object to be tested is a groove-shaped part with complex surface geometric features. In order to scan the entire part shape accurately and efficiently, the following constraints can be met when the 3D scanner works [8]. The scanning constraint is shown in Figure 4.
$N_i$ and $P_i$ represent the unit normal vector of points and points on the surface being measured respectively, $Q$ represents the scanner, and $M_i$ indicates the bisector of the two laser boundary scanning lines. The constraint analysis is as follows:

1) Scanner tilt:

The important assumption of laser triangulation scanner scanning is that the emergent ray is collinear with the normal vector at the point to be scanned, but this situation is difficult to achieve in the actual measurement process. There is usually an angle $\beta$ between the emergent ray and the normal vector. In order to obtain measurement effectively, this angle can not exceed the limitation.

Therefore, the angle between the scan point $P_i$ to the scanner's projection lens $Q$ and the scan point normal vector $\overrightarrow{N_i}$ can be less than the constraint angle $\gamma$.

$$\cos \langle \overrightarrow{d_i}, \overrightarrow{N_i} \rangle \geq \cos(\gamma)$$ (2)

Unit vector in the formula:

$$\overrightarrow{d_i} = (Q - P_i) / ||Q - P_i||$$ (3)

2) Field of view (FOV)

The scanning point can be within the range corresponding to the length of a certain laser stripe. The distance from the point on the surface of the measured object to the projection lens of the scanner is different. The scanning length of the effective stripe at different positions is also different, which is different from the ideal scanning situation shown in the Figure 4. The angle between $\overrightarrow{d_i}$ and $\overrightarrow{M_i}$ is $\alpha$:

$$\cos \langle \overrightarrow{d_i}, \overrightarrow{M_i} \rangle \geq \cos(\theta/2)$$ (4)

The angle of view $\theta$ in the equation is the fixed parameter of the scanner.

3) Depth of field (DOF)

The location of the scan point can be within the depth of field of the scanner, ie

$$h_s \leq ||Q - P|| \leq h_f$$ (5)

Among them, the far vision distance $h_f = h + l_{DOF}/2$ and the deep distance of myopia $h_s = h - l_{DOF}/2$, $h$ is the line-of-sight height (ie target distance) of the scanner projection lens and the scanning point of the surface of the object to be measured, $l_{DOF}$ is the depth of field distance of the scanner.

Since the measuring system adopts a grating projection three-dimensional scanner, the projected grating stripe can only be projected onto a part of the surface of the object to be measured. Therefore, for the scanner, the linearity of the structure near the optical center of the projection lens is better; In the binocular CCD vision system, an important parameter is the angle of view. This parameter determines the field of view of the CCD, which means the size of the image that the camera can capture. Thus, the closer to the vicinity of the optical center of the projection lens, the clearer the image is. Furthermore, the center of the scanner can be perpendicular to the surface of the part being measured during the measurement process in order to achieve the best projection.

2.4. Groove-shaped complex parts scanning path planning

The measured object for the measuring system is a groove-shaped part with complicated geometric features of the surface. The measurement system adopts a grating projection 3D scanner, and the scanner projects a vertical stripe grating projected on the surface of the part to be tested. In order to realize the three-dimensional shape scanning of the part, it is necessary to plan corresponding scanning path according to the shape of the part to be tested. The groove-shaped parts belong to the surface with
several complicated features. The main feature is except the frame part, the groove also has two vertical faces similar to the wall, and its shape is shown in Figure 5.

![Figure 5. Groove object and inner wall.](image)

In order to obtain a more complete three-dimensional shape of the part, the inner wall also needs to be scanned. For a scanning object such as a wall, the typical geometric feature is the intersection of two vertical planes of space. According to the measurement principle of the grating projection method and the characteristics of the projection grating, the grating stripe is required to maintain a vertical relationship with the edge of the wall to be tested. Combined with scanner constraint analysis, the intersection of the two vertical surface is shown in Figure 6:

![Figure 6. Scanning the intersection of two vertical faces.](image)

In the picture above, $S$ represents a raster three-dimensional scanner, and surface 1 is perpendicular to surface 2, $N_1$ and $N_2$ represents the normal of the two vertical faces respectively, indicating the effective scan length of the grating on both sides, and the relationship between the incident angle of the raster projection $\theta$ and the scan length $l$ is:

$$\theta = \frac{3}{4} \pi - \angle P_1 O = \frac{3}{4} \pi - \arctan\left(\frac{|S|}{|P_2|}\right) = \frac{3}{4} \pi - \arctan\left(\frac{\sqrt{2}|S|}{l}\right) \quad (6)$$

In the above formula, $|S|$ is the maximum depth of field value of the scanner. For the 3D scanner used in this measurement system, 500mm is used for $|S|$. The maximum angle $\theta$ of incidence when
scanning both surface is 60°, which can obtain the value of $l$ is 189mm. For groove-shaped parts, the groove depth is generally less than 20mm and the upper surface width of the wall is less than 25mm. According to this feature, the scanner projects the grating stripe plane on the surface of the part, which the size of the grating surface can cover the part.

When the two walls intersect and are on the upper surface of the part, so that complete the scanning of the two walls and reduce the extra path, the cross-scan is used to complete the scanning of one wall and then rotate the scanner. Scan 90° from the other side to complete the scanning of the entire upper surface. The scanning path is shown in Figure 7 (the letters in the picture represent each measurement point in the scanning path):

![Figure 7. Groove-shaped part scan path.](image)

Corresponding to the above figure, the scanning path of the groove-shaped part is: $a \rightarrow b \rightarrow c \rightarrow d \rightarrow e \rightarrow f \rightarrow g \rightarrow h$. Among them, between the path conversion from d to e, the scanner needs to be rotated vertically to complete the position conversion.

3. Results and discussion

According to the planning of the measuring path of the groove-shaped part completed in Section 2.4, combine the relationship between the incident angle of the grating projection and the scan length when the scanner scans the intersection of two perpendicular planes, mark the measurement points of the groove parts in the 3D measurement offline simulation (as shown in Figure 8), and then make the robot move to each planned measuring point by simulation. According to the optimal measuring distance of the 3D scanner, this experiment keeps the distance between the projection lens of the scanner and the part to be tested at about 500mm, then the program runs to obtain the simulation value of the robot pose in the scan path, which is shown in Table 1.

| Measuring points | Simulation value $(X, Y, Z / mm, R_x, R_y, R_z / ^\circ)$ |
|------------------|----------------------------------------------------------|
| a                | 1640.030,25.993,650.911,121.929,-22.072,77.729         |
| b                | 983.568,15.589,455.286,43.610,-19.123,109.886          |
| c                | 1217.994,19.304,636.344,88.524,-23.941,91.507          |
| d                | 792.802,12.565,399.232,48.572,-20.652,108.196          |
| e                | 1438.769,-367.208,571.244,133.118,-18.400,-18.540      |
| f                | 1392.315,397.977,450.652,44.616,-15.793,18.423         |
| g                | 1401.782,188.223,650.520,88.1715,-26.255,3.958         |
| h                | 1366.362,498.423,449.694,56.091,-10.537,22.334         |

$X, Y, Z$ represents the motion degrees of freedom along three orthogonal axes of x, y, and z.

$R_x, R_y, R_z$ represents rotational the degrees of freedom around three orthogonal axes of x, y, and z.
Figure 8. Measurement simulation.

After the simulation is completed, use the powerful post-processing function of the simulation software to generate the corrected robot program and download it to the real robot to complete the measurement of the groove part, which is shown in Figure 9 specifically. The robot moves to each measurement point and records the pose of the robot at this time. The measured values are shown in Table 2.

Table 2. Measuring path robot pose measurement.

| Measuring points | Measurement value \((X, Y, Z / \text{mm}, R_x, R_y, R_z / ^\circ)\) |
|------------------|---------------------------------------------------------------|
| a                | 1640.031,25.993,650.911,131.930,-22.072,77.729 |
| b                | 983.568,15.589,455.286,43.610,-19.114,109.885 |
| c                | 983.568,15.589,455.286,43.610,-19.123,109.885 |
| d                | 792.802,12.565,399.232,48.571,-20.652,108.197 |
| e                | 1438.769,-367.208,571.244,133.119,-18.400,-18.540 |
| f                | 1392.315,397.977,450.652,44.617,-15.793,18.423 |
| g                | 1401.782,188.223,650.520,88.172,-26.255,3.959 |
| h                | 1366.362,498.423,449.694,56.090,-10.538,22.338 |

\(X, Y, Z\) represents the motion degrees of freedom along three orthogonal axes of x, y, and z.

\(R_x, R_y, R_z\) represents rotational the degrees of freedom around three orthogonal axes of x,y, and z.

By comparing and analyzing the data in Table 1 and Table 2, the maximum position deviation between the real measurement path robot pose information and the simulation measurement path robot pose information is 0.001mm, and the maximum angle deviation is 0.009°. It is proved that the actual measurement path of the robot is basically the same as the simulation measurement path when the actual three-dimensional shape measurement of the groove-shaped complex parts is performed. This path planning method can obtain complete measurement information when performing three-dimensional shape measurement on groove-shaped complex parts.

After pre-process and encapsulate the measured 3D point cloud data, which is shown in Figure 10. The results show that the planned measurement path can completely restore the shape of the part under test, which also effectively preserves the shape of the groove of the part to be tested and the intersection of two vertical planes, and has the ability to measure complex groove-shaped parts. After the pre-pretreatment of the measured point cloud, the splicing process is performed. The measuring point cloud is spliced into a triangular mesh form, and then the CAD model of the workpiece is optimally fitted and aligned, which the 3D deviation analysis is performed. The deviation analysis result is shown in Figure 11. The color bar graph on the right in Figure 11 shows the distribution of the
deviation. The deviation analysis results show that the stitching precision of the point cloud is concentrated within 0.3mm, and the measurement accuracy can meet the requirements.

Figure 10. Data after processing the measured part.

Figure 11. Comparison of measured data of measured part.

4. Conclusions

Because the traditional measurement method and live work cannot meet the actual measurement demand, this paper proposes a new method to measure the path planning of groove-shaped complex parts. Based on the principle of raster scanning projection measurement, we explore the mathematical model of projection grating trigonometry theory. Moreover, according to the different characteristics of discrete geometric features such as walls and edges on the inside of grooves in groove-shaped complex parts, and we also study scanning constraints such as dip angle and depth of field of 3D scanner. According to the above analysis, the method of groove-shaped complex parts measurement path planning was presented. Finally, we verify the feasibility of this method by measuring the path planning experiment. The results show that the position deviation during the measurement is within 0.001mm and the angular deviation is within 0.009°, which proves the feasibility of the measurement path for the groove-shaped complex parts. Simultaneously, the stitching precision of the point cloud is concentrated within 0.3mm, and the measurement accuracy can meet the requirements.

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