Research on Robotic Measurement Path Planning for Complex Surface Workpieces

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Abstract. Combined with measurement efficiency, measurement accuracy and no interference in the measurement process, this paper proposes a path planning method for a measuring robot for complex surfaces such as blisk. The position planning of robot measurement path is realized based on the surface chord height difference, and the attitude planning of robot measurement path is realized based on the single measured point measurement attitude space(SMPMAS). Finally, the effectiveness of the proposed method is verified by experiments.

1. Introduction

Because the blisk and other complex surface parts are composed of multiple blades, adjacent blades have small spacing and poor openness. In order to ensure the measurement accuracy, measurement efficiency and prevent interference in the measurement process, it is necessary to study the planning of the measurement path. Among them, Song [1] used the 3+2 axis coordinate measuring instrument to measure the blisk in a point-by-point manner, but the region division algorithm needs to be improved. Sun, B. and Li, B. [2] derived a quantifiable error model from the angle error mechanism of the laser displacement sensor and proposed a rapid method to detect aero-engine blade form [3], which controlled the error within 10 μm. Li, K. et al. [4] proposed an algorithm model based on contour measurement with constant height, which required setting of interpolation times and upper limit of angle. Zang, Y. et al. [5] proposed a simplified method based on multi-level strategy, which provided a new scheme for optimizing the adaptive laser scanning of free-form surface point cloud.

Although the more work points measured, the higher the accuracy of the reconstructed surface, however, in order to improve the measurement efficiency, it is necessary to reduce the number of detection points and conduct reasonable sampling of the measurement points, that is, position planning. Secondly, the overall structure of the blisk is complex. In order to ensure that no interference occurs during measurement, the characteristics of the point laser sensor should be fully considered. The attitude planning of the measurement point is also very important. The solution of these core problems is of great significance to the effective measurement of complex surface workpieces such as blisk and to ensure the measurement accuracy. In this paper, based on the measurement efficiency, measurement accuracy and the absence of interference in the measurement process, a method of robot measurement path position and attitude planning for complex surfaces such as blisk was proposed. The effectiveness of the method was verified by experiments.
2. Position Planning of the Blisk Measurement Operation Point Based on CAD Model

Free-form surface is a kind of geometric element that is difficult to define and process. It is difficult to detect the blade profile of the blisk with free-form surface. The distribution planning of measurement points is one of the main contents of free-form surface measurement. The planning according to the curvature of the surface can effectively improve the accuracy and efficiency of measurement.

2.1. Parametric Representation of the Surface

Let \( u \) and \( v \) be the parameters of surface \( S \), the parametric equation of surface \( S \) can be expressed as:

\[
\mathbf{r} = \mathbf{r}(u, v) = \{x(u, v), y(u, v), z(u, v)\}
\]

(1)

Let \( P_0(u_0, v_0) \) be any point on the surface \( S \), let \( u = u_0 \), and let \( v \) vary, then a curve on the surface \( S \) is traced by the moving point, which is called the \( v \) line of the surface passing through \( P_0 \), and its equation is:

\[
\mathbf{r} = \mathbf{r}(u_0, v) = \{x(u_0, v), y(u_0, v), z(u_0, v)\}
\]

(2)

And similarly, when \( v = v_0 \) there is the \( u \) line of the surface that goes through \( P_0 \). Therefore, every point on the surface \( S \) has a \( u \) line and a \( v \) line, and these \( u \) and \( v \) lines constitute a parametric curve network on the surface.

2.2. Surface Geodesic and Surface Chord Height Difference

Geodesic is one of the most important curves on a surface. For any given points \( P \) and \( Q \) on the surface \( S \), there will be an infinite number of curves on \( S \) that pass through points \( P \) and \( Q \). The curve with the shortest length in the local range is called the geodesic of points \( P \) and \( Q \) on the surface \( S \). The curvature of the geodesic can reflect the curvature of the surface between the two points. At the same time, there is a line connecting points \( P \) and \( Q \), and the maximum distance between each point on the geodesic and this line is called the surface chord height difference between points \( P \) and \( Q \), as shown in Fig. 1.

![Fig. 1. Diagram of geodesic and surface chord height difference](image)

2.3. Position Planning Strategy for Measurement Points

At present, the position planning of measurement points on the curved surface is generally realized by using the method of first planning the line and then planning the points on the planned line. However, there are some problems in this method. First, the degree of curvature of the surface is not fully considered when planning the line. Second, when planning points, even though the curve chord height difference method is adopted to consider the bending degree of the line, it cannot fully reflect the bending degree in the adjacent area of the curved surface where the line is. In this section, the \( uv \) curve of the surface is effectively combined with the geodesic, and a position planning strategy based on the surface chord height difference is proposed.

As shown in Fig. 2, \( P_i \) is used to represent the measurement points, \( i \in [1, M] \), \( j \in [1, N] \), which are the values of \( v \) direction and \( u \) direction respectively. Assume that the measurement process first proceeds along the \( v \) direction of the surface. The detailed description of the position planning process of the measurement point is as follows:

1. Take a boundary \( v \) line \( \mathbf{r}(1, v) \) on the surface \( S \).
2. Take any point on one end of \( \mathbf{r}(1, v) \) as the first measurement operation point \( P_1 \), and
determine the next measurement operation point \( P_2 \) with the rule as shown in Fig. 3, that is, by setting the empirical values \( \varepsilon_1, \varepsilon_2, D \) and \( \Delta P \), make the surface chord height difference solved within the ideal threshold range.

(3) Repeat the above process to obtain all measurement points \( P_i \) on a measurement path, as shown in Fig. 2(a).

(4) Make each \( u \) line \( r(u,i) \) of surface \( S \) through each measurement point \( P_i \), as shown in Fig. 2(b).

(5) Adjust the process of Step (2) to get adjacent measurement operation points \( P_i \) on each \( u \) line \( r(u,i) \), as shown in Fig. 2(c).

(6) Fit into a space curve through each \( P_i \) point and project this curve onto the surface \( S \), as shown in Fig. 2(d) and (e), \( L_2 \) is obtained.

(7) New \( P_i \) on \( L_2 \) is obtained by repeating the rules shown in Fig. 3, as shown in Fig. (f) and (g).

(8) Repeat (4)-(7) until all measurement points of all fitting curves \( L_j \) on the surface \( S \) are obtained, as shown in Fig. 4.

**3. Attitude Planning of the Blisk Measurement Operation Point Based on CAD Model**

Because of the complexity of the structure of the blisk, the interference between the laser line and the measured blade or the laser sensor and the adjacent blade will occur when the point laser sensor is used to measure the blade. The existence of these problems may cause the measurement points planned in Section 2.3 to be invalid, so it is necessary to plan the attitude of the blisk measurement path.
3.1. Analysis and Classification of Single Measured Point Measurement Attitude Space (SMPMAS)

According to the measurement requirements of the point laser sensor, the laser line can have a certain angle with the normal line of the measured surface. That is, in the measurement coordinate system established as shown in Fig. 5(a), there are $R_{x}^{1} < R_{x} < R_{x}^{M}$, $R_{y}^{1} < R_{y} < R_{y}^{N}$. $R_{x}$ and $R_{y}$ are respectively the rotation angles around the X and Y axes of the measurement coordinate system. $R_{x}^{1}$, $R_{x}^{M}$, $R_{y}^{1}$ and $R_{y}^{N}$ are respectively the maximum rotation angle allowed according to the measurement requirements. Therefore, when measuring at each measured point, a SMPMAS can be formed, denoted as $\mathbf{A}_{\text{ts}}^{i}$. Each measurement attitude is known as the SMPMAS elements, denoted as $N_{j}^{\text{ts}}$. Each $N_{j}^{\text{ts}}$ passing the normal line of the measured point is called the optimal measurement attitude space element, denoted as $N_{\text{opt}}^{\text{ts}}$. When $-R_{x}^{1} = R_{x}^{M} = 15^\circ$ and $-R_{y}^{1} = R_{y}^{N} = 15^\circ$, the SMPMAS obtained is shown in Fig. 5(b).

![Fig. 5. Measurement effect diagram of single measured point: (a) Single measured point measurement coordinate system; (b) SMPMAS.](image)

Taking related intervention into consideration, some $N_{j}^{\text{ts}}$ in $\mathbf{A}_{\text{ts}}^{i}$ may be invalid. $\mathbf{A}_{\text{ts}}^{i}$ with all $N_{j}^{\text{ts}}$ invalid is called invalid $\mathbf{A}_{\text{ts}}^{i}$, as shown in Fig. 6(a). $\mathbf{A}_{\text{ts}}^{i}$ containing at least one valid $N_{j}^{\text{ts}}$ is called valid $\mathbf{A}_{\text{ts}}^{i}$. In valid $\mathbf{A}_{\text{ts}}^{i}$, those $\mathbf{A}_{\text{ts}}^{i}$ that do not contain $N_{\text{opt}}^{\text{ts}}$ are called fully constrained valid $\mathbf{A}_{\text{ts}}^{\text{exa}}$, as shown in Fig. 6(b), denoted as $\mathbf{A}_{\text{ts}}^{\text{exa}}$. Call $\mathbf{A}_{\text{ts}}^{i}$ that contains $N_{\text{opt}}^{\text{ts}}$ and invalid $N_{j}^{\text{ts}}$ semi-constrained valid $\mathbf{A}_{\text{ts}}^{i}$, as shown in Fig. 6(c), denoted as $\mathbf{A}_{\text{ts}}^{\text{exn}}$. Call $\mathbf{A}_{\text{ts}}^{i}$ in which all $N_{j}^{\text{ts}}$ are valid unconstrained valid $\mathbf{A}_{\text{ts}}^{i}$, as shown in Fig. 6(d), denoted as $\mathbf{A}_{\text{ts}}^{\text{EN}}$.

![Fig. 6. Example diagrams of various types of SMPMAS: (a) invalid $\mathbf{A}_{\text{ts}}^{i}$; (b) $\mathbf{A}_{\text{ts}}^{\text{exa}}$: fully constrained valid $\mathbf{A}_{\text{ts}}^{i}$; (c) $\mathbf{A}_{\text{ts}}^{\text{exn}}$: semi-constrained valid $\mathbf{A}_{\text{ts}}^{i}$; (d) $\mathbf{A}_{\text{ts}}^{\text{EN}}$: unconstrained valid $\mathbf{A}_{\text{ts}}^{i}$.](image)

3.2. Determination of Valid SMPMAS Types

Let the currently measured blade profile body be $\mathbf{A}_{s}$, and its adjacent blade profile body be $\mathbf{A}_{s}^{-1}$ and $\mathbf{A}_{s}^{1}$ respectively. For valid $\mathbf{A}_{\text{ts}}^{i}$, a SMPMAS type criterion is described as follows:

(1) If $\mathbf{A}_{\text{ts}}^{i}$ has no intersection with either $\mathbf{A}_{s}^{-1}$ or $\mathbf{A}_{s}^{1}$, $\mathbf{A}_{\text{ts}}^{i}$ is $\mathbf{A}_{\text{ts}}^{\text{EN}}$, that is:

$$\mathbf{A}_{\text{ts}}^{\text{EN}} \sim (\mathbf{A}_{\text{ts}}^{i} \cap \mathbf{A}_{s}^{-1}) \cup (\mathbf{A}_{\text{ts}}^{i} \cap \mathbf{A}_{s}^{1}) = \emptyset$$

(3)
(2) If $A_i^{tts}$ has an intersection with $A_{s-1}$ or $A_{S_1}$, and $N_{opt_i}^{tts}$ has no intersection with either $A_{s-1}$ or $A_{S_1}$, then $A_i^{tts}$ is $A_i^{tts\_en}$, that is:

$$A_i^{tts\_en} \sim ((A_i^{tts} \cap A_{s-1}) \cup (A_i^{tts} \cap A_{S_1}) \neq \emptyset) \land ((N_{opt_i}^{tts} \cap A_{s-1}) \cup (N_{opt_i}^{tts} \cap A_{S_1}) = \emptyset)$$ (4)

(3) If $A_i^{tts}$ has an intersection with $A_{s-1}$ or $A_{S_1}$, and $N_{opt_i}^{tts}$ also has an intersection with $A_{s-1}$ or $A_{S_1}$, then $A_i^{tts}$ is $A_i^{tts\_ea}$, that is:

$$A_i^{tts\_ea} \sim ((A_i^{tts} \cap A_{s-1}) \cup (A_i^{tts} \cap A_{S_1}) \neq \emptyset) \land ((N_{opt_i}^{tts} \cap A_{s-1}) \cup (N_{opt_i}^{tts} \cap A_{S_1}) \neq \emptyset)$$ (5)

3.3. Attitude Planning Strategy for Measurement Points

The goal of attitude planning strategy for measurement points is to find the smallest angle attitude $N_j^{tts}$ between a laser line and the normal lines of the surface passing through this point, at the same time ensure the laser line and the blisk other blade surface without interference at the measurement operation point of each blade. If there is interference in the normal direction $N_{opt_i}^{tts}$, then the attitude with the minimum valid angle is taken and the principle of minimum laser offset is followed, denoted as $N_{min_i}^{tts}$. The specific implementation process is shown in Fig. 7:

1. Determine $A_i^{tts}$ of each measured point according to the point laser sensor measurement requirements.
2. According to the determination principle, determine the types of each $A_i^{tts}$.
3. According to the different type of $A_i^{tts}$, choose the corresponding elements $N_j^{tts}$ as the attitude of the measured point.

Fig. 8 is the result of attitude planning for a measurement path of a blade on the blisk according to the above planning strategy. From the planning result, the attitude planning strategy proposed in this paper can effectively avoid the occurrence of interference phenomenon in the measurement process.

Fig. 7. Flowchart of attitude planning strategy of measurement operation point; Fig. 8. Attitude planning results of measurement points on a single measurement path

4. Measurement Experiment of Blade Profile of Robotic Aero-engine

4.1. Experiment Platform

As shown in Fig. 9, the experimental system is composed of industrial robot, point laser sensor and measured blade, etc. The model parameters are shown in Table 1 below. Among them, the ABB140 robot
has the advantages of strong reliability, fast speed and high precision, which has been widely used in many industrial occasions. The OPTEX CD5-85 laser displacement sensor has extremely high resolution and stability, which can be used for stable detection of different materials. It is suitable for measuring the working accuracy of complex surfaces such as blisk. The blade is shown in Fig. 10. The blade of a certain type of aeroengine is taken as the experimental object to carry out the real experiment.

![Composition diagram of experimental system](image1)

![Physical picture of measured blade](image2)

Fig. 9. Composition diagram of experimental system

Fig. 10. Physical picture of measured blade

| Table 1 System hardware model parameters |
|-----------------------------------------|
| Robot                                   | Model | Load   | Effective working radius | Repeated positioning accuracy |
|-----------------------------------------|-------|--------|--------------------------|-----------------------------|
| ABB140                                  |       | 6kg    | 810mm                    | ±0.03mm                     |
| Point laser sensor                      | Model | Effective detection range | Resolution ratio | Linear precision |
| OPTEX CD5-8                             |       | 85±20mm | 1μm                      | ±0.05%F.S.                |

4.2. Experimental Process and Results

The purpose of this part of the experiment is to verify the effectiveness of the blisk measurement point location planning strategy based on CAD model proposed in this paper, and analyze the measurement efficiency and surface reconstruction accuracy of different sampling strategies through the measurement results. In order to simplify the experimental process, the uniform sampling strategy was firstly used to carry out intensive measurement on the blade profile, and then different sampling strategies were used to sample the original measurement data. Finally, the results were compared and analyzed.

![Experimental process and results](image3)

Fig. 11. Experimental process and results: (a) Path planning result; (b) Blade profile measurement result; (c) Uniform sampling result; (d) Surface chord height difference sampling result; (e) Surface reconstruction results of uniformly sampled data; (f) Surface reconstruction results of sampled data of surface chord height difference; (g) Error analysis result of uniform sampling data; (h) Error analysis result of sampling data of surface chord height difference.
The specific implementation process and results are as follows:
(1) Carry out intensive blade measurement path planning, and the results were shown in Fig. 11(a).
(2) Online measurement was conducted on the system shown in Fig. 9, and the measurement results were shown in Fig. 11(b).
(3) Sampling and analysis of measurement results were carried out by using uniform sampling and surface chord height difference method proposed in this paper. 2000 sampling points were selected, and the results were shown in Fig. 11(c) and (d).
(4) The sampled data were reconstructed to obtain the blade triangular surface. The reconstructed surface results were shown in Fig. 11(e) and Fig. (f).
(5) Error analysis was conducted between the original data and the reconstructed surface, and the results were shown in Fig. 11(g) and Fig. (h).
(6) Select different the number of sampling points (800, 50) to repeat step (3)-(5), and the comparison results of mean square deviation of reconstructed surfaces with different sampling methods were obtained, as shown in Fig. 12 below.

It can be seen that with the same sampling points, the reconstruction error of the proposed surface chord height difference method is relatively small, and the advantage is more obvious when the sampling points are small.

Fig. 12. Reconstruction error analysis diagram of different sampling methods

5. Summary and Discussion
Combined with measurement efficiency, measurement accuracy and no interference in the measurement process, this paper proposed a path planning method for a measuring robot for complex surfaces such as blisk. It includes position planning based on surface chord height difference method and attitude planning based on SMPMAS method, and achieves good results compared with the traditional uniform sampling experiment. It can be applied to non-contact path planning of complex surfaces such as blisk, and has certain universality.

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