Adaptive Positioning Repair Method for Aero-Engine Blades by Using Speckle Vision Measurement

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ABSTRACT The repair of damaged aero-engine blades has an extremely high economic value. Due to the complexity of the blade surface and various kinds of deformation during the lifetime, blade positioning in the repair process has always been one of the key problems in the aviation industry. In this study, a method of blade self-adaptive positioning repair method based on speckle vision measurement is proposed. Firstly, a speckle vision measurement system is established to measure the speckles coated on the damaged blade surface to obtain its surface point cloud. Meanwhile, the coordinates of the reference points on the fixture are obtained to build the relative pose model between the blade and the fixture. Secondly, through the solution of posture relations among the mark point coordinate system, measuring camera coordinate system, probe coordinate system, and machine coordinate system, the self-adaptive positioning of the under-positioning clamping blade in the machine coordinate system is achieved. Then based on the positioning model, the machining repair parameters are selected reasonably to complete the CNC (Computer numerical control) path planning of tool repair. Finally, the DMU five-axis numerical control center was used to carry out adaptive positioning repair experiments on the damaged blades. The experimental results showed that this method could achieve satisfying repair effect in under positioning clamping, and provide a new method for repairing damaged aero-engine blades.

INDEX TERMS Repair for damaged blades, speckle vision measurement, adaptive positioning, CNC repair path planning.

I. INTRODUCTION Aviation engine blades, one of the core components of turbo aero-engine will easily lose the good aerodynamic performance due to the bad working environment in which the blades will form various damage, such as distortion, wear, cracks, and dents, etc. [1], [2]. Complex preparation process and materials which are especially hard to machine lead to the high cost of blades. To prolong the service life of these aero-engine parts, it is more economical to repair damaged blades [3], [4]. In the repair process of conventional engine blades, the damaged parts are generally removed firstly, then the laser cladding technology is used to weld or overlay the blades. Finally, the welded blades are subjected to material reduction to meet the aerodynamic performance requirements [5], [6].

In the process of blade repair, it is vitally important to keep the geometry of the blade and restore its maximum efficiency. The blade is prone to creep in the long-term use, so the original engine blade model of the design company is
difficult to apply to the damaged blade model to be repaired. At the same time, due to the complex shape of the blade surface and various damage forms, the traditional fixture positioning cannot meet the positioning requirements of the material reduction, so it is difficult to achieve the milling repair of the redundant materials after laser cladding of the damaged blade. In recent years, with the development of measurement technology and numerical control technology, the self-adaptive positioning repair of the blade has been concerned. At present, the traditional laser measurement and visual scanning method are relatively common methods for blade measurement, which have fast measurement speed and high efficiency. However, there are more point cloud data and more noise points in the measurement points, so a large number of data processing is needed to complete the blade model construction [7]. Meanwhile, the traditional blade repair laser cladding area grinding and polishing needs a lot of manpower and material resources. And the repair process depends on the operator’s experience and skills which lead to random repair results.

The CNC machining center is a useful tool to restore the geometry of the damaged blade by self-adaptive positioning and removing the surplus material of laser cladding. The key problem is to use the speckle vision measurement method to measure the damaged blade in three dimensions to get the measured point cloud data and establish the blade model to be repaired. Then, the self-adaptive positioning of the complex curved blade in the machining center under the condition of under-positioning clamping (non-proprietary fixture positioning) will be achieved and the milling repair of the CNC center will be completed. For the blade self-adaptive positioning repair, some domestic and foreign academic institutions have also carried out relevant research, the process roughly includes data measurement, reverse modeling, welding filling, CNC repairing [8], [9]. Bremer [10], [11] proposed a repair system based on reverse engineering. A touch-trigger probe, inspection technology, and milling operation with modifying the master cutting path model were the basis of the system. Yilmaz et al. [12] proposed a method of measuring blade data based on a 3D non-contact digital system, which can effectively remove redundant welds by reconstructing the blade surface model and can be used for repair and overhaul of complex geometry and expensive components. Zhao et al. [13] studied the geometric reconstruction method for the common service blade defects and gave the CNC machining tool path suitable for the self-adaptive repair of the damaged blade on this basis. The TTL organization of Starrag group developed an adaptive repair process, which used a CNC measuring machine equipped with stripe laser measurement to scan data and analyze it by adaptive machining. The adaptive application processing program can complete blade repair after digitizing the blade contour of tip welding in a short time. Since the use of intelligent self-adaptive positioning repair technology to repair and remove a small part of redundant cladding materials at any position of the blade, it is necessary to explore the self-adaptive positioning of complex surface parts in the machining center.

To solve the problem of workpiece positioning in the process of blade self-adaptive positioning and repair, a great deal of research has been studied. Vergeest et al. [14] studied the machining and positioning method of the free-form surface without feature points, realized the positioning of the free-form surface by matching real-time 3D scanning points with CAD model, and then completed the machining of the free-form surface with six degrees of freedom robot. Yan et al. [15] used a similar two-level optimization method to achieve rough positioning by matching the difference between Gaussian curvature and average curvature, and then achieve accurate positioning of complex surfaces. Wu [16] studied an adaptive positioning method of repaired blades for model reconstruction and CNC machining. By establishing a mathematical model to describe the positioning under the constraint conditions, the positioning method of the repaired blade for CNC machining was achieved based on the proposed mathematical model and the continuity of the deformation process. Most of the above researches focus on the positioning of curved parts, but there are some problems in the application of this idea to the adaptive positioning and repair of aero-engine blades. Firstly, the original model of blades is difficult to obtain, and the blades will creep after use, so it is difficult to apply to the blades to be repaired. Secondly, the geometry of blade surfaces is complex and the damage forms are diverse, so it is difficult to achieve the accurate self-adaptive positioning repair of the blades in the CNC center.

Aiming at the self-adaptive positioning repair of the damaged blades, this paper proposes a method of self-adaptive positioning of blades by using speckle vision measurement with a five-axis machining center after laser cladding. Therefore, the tool repairing path of the redundant cladding area of blades is planned based on the positioning relationship. The paper is organized as follows. Section II describes the overall process of blade adaptive positioning repair. In section III, the three-dimensional point cloud data of damaged blades are measured by speckle vision, and then the blade configuration to be repaired is obtained. In section IV, the adaptive positioning principle and solution method of a damaged blade with the complex curved surface are described. Section V provides the tool repairing path for damaged blades to remove excess cladding material. Section VI provides a static experimental verification of speckle measurements. Section VII provides the experimental verification of the adaptive positioning repair of the blades, which proves the feasibility of the proposed method. Finally, a brief conclusion is given in Section VIII.

II. BLADE ADAPTIVE POSITIONING REPAIR PROCESS

The blades are prone to creep in the long-term use process. At the same time, the blade shape is complex and the position of damage is random. Therefore, it is necessary to carry out adaptive positioning when using the numerical control system
to reduce the material and restore the complex curved blades. That is to say, the blade is fixed first and then positioned. Although the blade has arbitrary shape and damage, multi-axis milling repair path planning is carried out to complete the blade repair. It is usually implemented according to the process shown in Fig.1. Firstly, the blade and the positioning points are measured by visual measurement. Secondly, the reconstruction of the blade model to be located and the solution of the adaptive model is completed, and the adaptive positioning of the blade is completed by data intersection. Finally, the repair path planning of redundant cladding materials in the area to be repaired is carried out according to the positioning data of blade, and the adaptive positioning repair of the damaged blade is completed.

III. ACQUISITION OF THE MODEL TO BE REPAIRED
A. POINT CLOUD ACQUISITION METHOD BASED ON SPECKLE MEASUREMENT

Obtaining the real blade surface is the first step of the proposed method. In the process of the experiment, matte paint speckles need to be sprayed on the blade surface first. The speckles are easy to be cleaned by paint remover and do not affect the secondary use of the blade. Meanwhile, spray speckles have the advantages of strong randomness, moderate quantity and strong follow-up, which reduces the data amount of point cloud measured by contact measurement, simplifies the tedious steps of traditional visual measurement in projecting feature light strips on the blade surface and pasting mark points and solves the problem that the projected feature light strips cannot follow the workpiece to achieve accurate measurement and positioning. To obtain the precise configuration of the blade surface, a visual measurement system is established. Fig. 2(a) is the schematic diagram of the visual measurement system. The angle between the optical axis of the left camera and the right camera $\theta_r$ is $25^\circ \sim 40^\circ$. After the speckles are illuminated by the lighting device, two measuring cameras image them respectively to form a certain stereo parallax. The three-dimensional spatial coordinates of the speckles on the surface of the blade are calculated by using the imaging point coordinates of the speckles on the left and right image planes to achieve the binocular stereo vision measurement [17], [18].

The traditional matching method needs to extract the feature descriptors of speckles and then uses the distance criterion to match, but it takes a long time, so it is not suitable for measuring the surface speckles of curved blades. Therefore, the target tracking algorithm based on the optical flow method (Kanade-Lucas-Tomasi, KLT) is used to achieve the initial matching of speckle. Based on the initial matching, the epipolar constraint is used to eliminate the mismatched speckles in the matching process to further improve the matching accuracy, and the final matching of the speckles on the left and right image planes is completed [19], [20].

Due to certain errors in the camera parameters, speckle image coordinates, and the relative orientation of the two cameras, the speckle matching point projection lines corresponding to the triangle intersection principle cannot accurately intersect, that is, there is a convergence error, and the left and right camera intersection lines cannot accurately intersect at one point, as shown in Fig. 2 (b). Therefore, the problem of solving the coordinates of space points is transformed into a distance optimization problem.

Minimize the sum of the squares of the distance from the point to its projection line as the optimization goal, where $P (X, Y, Z)$ is any spatial point, $O_l \left( X_{O_l}, Y_{O_l}, Z_{O_l} \right) O_r \left( X_{O_r}, Y_{O_r}, Z_{O_r} \right)$ are the light center of the left and right cameras, $p_l \left( x_l, y_l \right), p_r \left( x_r, y_r \right)$ are characteristic image points of the left and right cameras. $v_l$ is the normalized vector of the projective ray that goes through $O_l$ and $p_l$, similarly $v_r$ is the normalized vector of the projective ray that goes through $O_r$ and $p_r$. The total distance $H$ between the spatial feature point and two projective rays can be represented as:

$$H = \| PM \|^2 + \| PN \|^2 \quad (1)$$

The nonlinear optimization method is used for (1). $H$ is finally obtained which is the spatial coordinates that minimize the sum of the squared distance between the point and the projective rays. Through the above-mentioned spatial coordinate calculation process, the point cloud data of the blade surface can be obtained.
Due to the complexity of the surface morphology of the measured blade and the limitation of the camera’s single measurement field, it is impossible to extract the whole 3D point cloud coordinate data of the blade to be measured at one time, so multi-angle measurement is performed. For the coordinate extraction of the mark points, the image processing processes such as graying, gaussian smoothing, thresholding, canny edge extraction, and ellipse centroid extraction are carried out for the blade image taken at different positions. After matching, the coordinates of the mark points are obtained according to the point cloud extraction method, and then through the point cloud splicing based on the mark points, all the measurement data are unified in the same coordinate system, realizing full-visual three-dimensional splicing to obtain the blade point cloud data [21], [22].

B. DIGITAL BLADE MODELING

Firstly, the curvature of the whole part of the point cloud of the blade is estimated by the paraboloid fitting method of the local neighborhood, and then the boundary points of the point cloud of the blade are extracted based on the obtained curvature change law of the blade. Then, according to the theory of cubic B-spline, the curve and surface of the blade are fitted, and the damaged blade model is obtained. Then the complete configuration of the blade is obtained through the surface extension to provide the model basis for the adaptive positioning and fixed-point repair of the blade [7].

IV. ADAPTIVE POSITIONING OF THE COMPLEX CURVED BLADE

A. PRINCIPLE OF ADAPTIVE POSITIONING

Due to the complex geometry of the blade surface and the variety of damage forms, it is difficult to achieve accurate positioning in a five-axis machining center. Therefore, an adaptive blade positioning method using speckle vision measurement was constructed. Fig.3 is the schematic diagram of the adaptive positioning system. The blade under-positioning is clamped on the platform of the five-axis machining center, and the visual measurement system is placed in front of the machining center to measure and extract the shape and position information of the blade. The measurement data information is processed and calculated by the computer to obtain the adaptive positioning data information to realize the adaptive positioning of the blade under-positioning clamping [23].

The simplified geometric model of blade adaptive positioning based on visual measurement is shown in Fig. 3. Set $O \rightarrow x_P y_P z_P$ as the mark point coordinate system $P$, $O \rightarrow x_G y_G z_G$ as the measuring camera coordinate system $G$, $O \rightarrow x_D y_D z_D$ as the probe coordinate system $D$, $O \rightarrow x_W y_W z_W$ as the machine coordinate system $W$. The essence of adaptive positioning is to find out the position coordinates of the blade point cloud in the machine coordinate system.

The relationship between the coordinate $x_P$ of a point on the blade surface in the coordinate system of the mark point and the coordinate $x_W$ of the same point in the machine coordinate system is

$$x_W = \frac{W}{\rho} P \cdot D_T \cdot G_T \cdot x_P \quad (2)$$

where $G_T$ is the pose matrix of the mark point coordinate system under the measuring camera coordinate system; $D_T$ is the pose matrix of the measuring camera coordinate system under the probe coordinate system; $\frac{W}{\rho} P$ is the pose matrix of the probe coordinate system under the machine coordinate system matrix. Each of the pose matrices can be composed of a rotation matrix $R$ and a translation matrix $T$ between coordinate systems, so equation (2) is written as

$$\begin{bmatrix} x_W \\ 1 \end{bmatrix} = \begin{bmatrix} R_D & T_D \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} R_G & T_G \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} R_P & T_P \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_P \\ 1 \end{bmatrix} \quad (3)$$

Through the above coordinate operation, the coordinate information of each point of the blade in the coordinate system is obtained. Therefore,
system of the mark point is converted to the coordinate system of the machine, and the adaptive positioning of the blade with a complex curved surface can be realized.

B. POSE SOLUTION OF ADAPTIVE POSITIONING MODEL

To solve the self-adaptive positioning model, each pose coordinate system should be established, the position information of each spatial reference measurement point should be measured by the above-mentioned visual measurement method, and then the self-adaptive positioning model should be solved.

1) POSE SOLUTION OF MARK POINT COORDINATE SYSTEM IN THE COORDINATE SYSTEM OF MEASURING CAMERA

Mark point coordinate system is established by the three-point method. Mark point block is arranged on the fixture of the machine tool. Three reference mark points \( P_1, P_2, P_3 \) are selected. The distance is assumed to be known and \( P_1 P_2, P_1 P_3 \) is perpendicular to each other. \( P_1, P_2, P_3 \) is the measurement point obtained by visual measurement method, that is, the coordinate value under the coordinate system of the measuring camera. Now, the virtual mark point coordinate \( P_4 \) is added, and its coordinate is obtained by uniting \( P_1 P_2, P_1 P_3 \) cross products, and the coordinate system \( O \) is established by orthogonal vector \( P_1 P_2, P_1 P_3, P_1 P_4 \), where the unit vectors of the axis \( x, y, z \) are

\[
\begin{align*}
  n_x &= \frac{P_1 P_3}{|P_1 P_3|} \\
  n_y &= \frac{P_1 P_2}{|P_1 P_2|} \\
  n_z &= \frac{P_1 P_3 \times P_1 P_2}{|P_1 P_3 \times P_1 P_2|}
\end{align*}
\]

(4) \hspace{1cm} (5) \hspace{1cm} (6)

It is assumed that the construction mode of the coordinate system of the measuring camera is similar to this, all of which are right-hand coordinate systems, and the corresponding points \( P_1, P_2, P_3, P_4 \) are \( P_{G1}, P_{G2}, P_{G3}, P_{G4} \) respectively. Therefore, the conversion relationship between the coordinate system of the mark point \( O \) and the coordinate system of the measuring camera \( O \) is realized by a rotation matrix \( R_P \) and a translation vector \( T_P \), as shown in (7) and (8).

\[
\begin{pmatrix}
  x_G \\
  y_G \\
  z_G
\end{pmatrix} = R_P \begin{pmatrix}
  x_P \\
  y_P \\
  z_P
\end{pmatrix} + T_P = \begin{pmatrix}
  r_{11} & r_{12} & r_{13} \\
  r_{21} & r_{22} & r_{23} \\
  r_{31} & r_{32} & r_{33}
\end{pmatrix} \begin{pmatrix}
  x_P \\
  y_P \\
  z_P
\end{pmatrix} + \begin{pmatrix}
  t_1 \\
  t_2 \\
  t_3
\end{pmatrix}
\]

(7)

\[
\begin{align*}
  R_P P_1 + T_P &= P_{G1} \\
  R_P P_2 + T_P &= P_{G2} \\
  R_P P_3 + T_P &= P_{G3} \\
  R_P P_4 + T_P &= P_{G4}
\end{align*}
\]

(8)

From the above, the transformation matrix \( R_P \) and \( T_P \) can be obtained and then \( G_T \) is calculated.

2) POSE SOLUTION OF THE MEASURING CAMERA COORDINATE SYSTEM IN THE PROBE COORDINATE SYSTEM

The method of solving the pose matrix of the measuring camera coordinate system under the probe coordinate system is similar to the pose relationship solution method in 1). Firstly, the coordinate system of the machine tool probe is established. The difference is that the measurement coordinates of the machine tool probe in three reference positions are obtained by using the method of five-axis machine tool probe combined with the visual measurement. The specific operation method is to control the probe to be located at a suitable position from the blade by the machine tool first and capture the position information of the probe at this position after taking the image data. Then control the machine tool probe to translate a certain distance in the \( y \) direction to a relatively suitable position from the blade, and also extract the probe position information at this position. According to this method, extract the position information of the center point \( P_1, P_2, P_3 \) of the machine tool probe in three specific positions in turn. Assuming that the distance is known and \( P_1 P_2, P_1 P_3 \) is perpendicular to each other, the probe coordinate system \( O \) is established according to the three-point method. According to the method of vision measurement, when the image data of the machine tool probe is taken, the coordinate data under the coordinate system of the machine tool when three reference points of the probe are located is recorded by the data display function of the machine tool probe. While taking the machine tool probe image data according to the visual measurement method, the machine tool’s probe data display function is used to record the coordinate data values of the machine coordinate system when the probe is at three reference positions.

The corresponding reference points in the probe coordinate system and the measuring camera coordinate system are \( P_{D1}, P_{D2}, P_{D3}, P_{D4} \) respectively, and the conversion relationship between the probe coordinate system \( O \) and the measuring camera coordinate system \( O \) is also realized by a rotation matrix \( R'_{G} \) and a translation vector \( T'_{G} \). After the rotation and translation matrix is obtained, \( G_T \) can be obtained by (9).

\[
D^G_T = \begin{bmatrix} R'^{-1}_G & -R'^{-1}_G \cdot T'_G \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} R_G & T_G \\ 0 & 1 \end{bmatrix}
\]

(9)

3) POSE SOLUTION OF PROBE COORDINATE SYSTEM IN THE MACHINE COORDINATE SYSTEM

To solve the pose matrix of the probe coordinate system in the machine coordinate system, the pose of the five-axis machining center machine coordinate system should be described first. According to the principle of the internal establishment of the machine coordinate system of five-axis machining center, the machine coordinate system is established.
The machine control panel displays the spindle as the position coordinate under the machine coordinate system, controls the spindle to return to the coordinate origin, and takes this point as the coordinate origin, and then establishes the right-hand coordinate system with the positive axis direction and the positive axis direction of the machine respectively. According to the principle of the internal establishment of the machine coordinate system of five-axis machining center machine tool by coordinate operation, and the only determination of the position information of any point in the blade under the machine coordinate system is realized, that is, the adaptive positioning of the blade is realized by the method of visual measurement.

V. ADAPTIVE LOCATION REPAIR TRAJECTORY PLANNING

A. REPAIR STRATEGY

To effectively remove the excess cladding material during the laser cladding process of the blade repair surface, a suitable CNC machining equipment (Demag 5-axis machining center DMU 85 monoBLOCK and 3D Control Heidenhain TNC 640 system) was selected for adaptive positioning Milling repair. The established repair strategy mainly includes the selection of milling methods, tools and cutting parameters, and the generation of tool paths. The purpose of blade self-adaptive positioning repair is to develop a repair strategy to remove redundant materials from the blade corners and restore the geometric attributes before blade repair.

The blade repair process has the same geometrical requirements as shape and position, process size, surface roughness, and the like of conventional parts processing. The hardness of the blade to be repaired is strengthened after laser cladding repair. During the repair process, high temperature may occur and lead to wear at the contact between the tool and the cladding area. Therefore, the repair steps are determined as rough machining repair, semi-finishing machining repair and finishing machining repair, and the excess welding material is cut layer by layer. According to NX UG software as the generation environment of tool path, the path planning of blade repair is carried out.

To facilitate the subsequent generation of the adaptive positioning milling path, the missing parts of the blade to be repaired after laser cladding are filled. Because the laser cladding area is irregular, it is simplified for milling trajectories. See the trajectory planning section for the simplified model.

B. MILLING METHODS AND TOOLS

While removing the excess material of the blade after laser cladding repair, the top surface of the blade is repaired using...
the isoparametric method principle. Since the modeling of the blade cladding area in the early stage is slightly larger than the actual blade top contour, the method of the peripheral contour can complete the top milling repair. The tool cannot touch the blade when starting a new step during the repair operation, release it after completing each milling operation on the top, and then approach the blade from the same position for milling to avoid bending effects caused by cutting forces. Fig. 4 (a) is a schematic diagram of top milling.

For side milling operations, isoparametric milling is used to remove excess material in the cladding area, and a parameterized smooth tool path can be generated. In this case, the machining feature is the surface of the redundant cladding area of the blade to be repaired, to generate the correct tool path. Only the redundant cladding materials in the laser cladding area of the repaired blade need to be removed by self-adaptive positioning repair path planning, and the areas without laser cladding need not be repaired to reduce the unnecessary repair path travel. Although the fixed-point repair of the redundant cladding layer is carried out after multiple retreating and feeding, the repair efficiency of the blade is also improved to a certain extent. Fig. 4 (b) is a schematic diagram of side milling.

For different machining objects, appropriate milling tools should be selected to improve the efficiency and accuracy of blade self-adaptive positioning and repair. The purpose of this paper is to study and apply the method of self-adaptive positioning repair of blades, so a 45-material blade substrate that is easier to process is selected. A four-edge flat end mill with a diameter of 10mm is used to complete the milling repair of the entire blade. In semi-finishing and finishing repairs, the four-cutting edge can improve repair efficiency. The tool material is tungsten steel with a hardness of about 65HRC, which meets the milling requirements. According to the simplified modeling of the laser cladding area of the blade, the cutter can easily cover the cross-sectional area at the top of the blade to remove the cladding materials; and for the milling repair of the blade side, the side-blade contact line contact method can improve the repair efficiency, and at the same time reduce the cutting amount of each tool to reduce the bending effect caused by the excessive cutting force during the repair process.

C. MILLING PATH GENERATION

Machining operation parameters are mainly planning the tool paths while the cutting parameters are affecting the performance of the machining operation. All settings are made for the thin-walled complex geometric parts of the blade, and considering the precise geometry of the blade, reasonable settings need to be made. For the self-adaptive positioning repair machining of laser cladding blade, the recommended operation and cutting parameters were used at first. The main purpose was to remove the cladding deposits at the corners of the blade and restore its geometric shape. Therefore, the detailed parameter optimization design was not carried out. Based on the processability material characteristics of 45 cladding materials and previous experimental accumulation, the blade self-adaptive positioning repair processing parameters were selected. Table 1 shows the recommended parameters for blade repair.

All these parameter recommendations are set according to the geometric characteristics of thin-walled parts such as blades, using higher spindle speeds and lower feed rates, which are consistent with the machinability characteristics and thin sections of laser cladding materials geometry structure. The purpose of choosing a lower feed speed is to make the repaired surface have a better surface smoothness and to choose a smaller feed speed and back engagement to reduce the vibration, tool wear and deflection during the repair process. Moreover, the smoothness of approaching and retraction of the cutter to the blade are important issues in terms of the machining accuracy. Therefore, the tool is being approached and retracted by following an arc of a specified radius and angle.

After selecting the necessary parameters, the blade top milling and thin-wall side milling tool paths were generated on the characteristic surface of the blade to be repaired, and the paths were relatively smooth. The generated tool path directions were one-way, and the path interval was from top to bottom. According to the determined repair processing steps and cutting depth, only the tool path is generated in the parts to be repaired. Although the tool path is not continuous, the empty path is reduced and the repair efficiency is improved.

VI. THE STATIC EXPERIMENT

To ensure the accuracy of the blade self-adaptive positioning repair, the accuracy of the speckle vision measurement should be carefully evaluated firstly through a static measurement experiment.

The static experiment was implemented with a specimen whose position would be translated by a tri-axial table as shown in Fig. 5. The specimen is a damaged blade which is coated speckle pattern. The coordinates of these speckle points could be measured by using the binocular stereo vision...
system. The measured coordinate system is defined on the left camera. The x and y axis direct along with the pixel directions on the imaging sensor, while the z axis directs along the optical axis direction.

Then the specimen would be moved by the tri-axial table whose precision is 0.001mm along these three axes and the movement (2 mm) of the specimen would be measured at the same time. The experiment results are shown in Fig. 6. 1000 speckle spots have been chosen to evaluate the measurement accuracy. The average deviations along x, y, z directions were 0.003 mm, 0.012 mm, and 0.049 mm, respectively. While the standard deviations were 0.017 mm, 0.020 mm, and 0.029 mm, respectively. The static speckle measurement experiment showed that the errors in the three directions of x, y, and z remain at a low level, so the measurement accuracy can meet the blade repair application proposed in this paper.

VII. EXPERIMENTAL VERIFICATION OF BLADE SEIL-ADAPTIVE POSITIONING REPAIR

A. CONSTRUCTION OF THE EXPERIMENTAL SYSTEM

To verify the reliability and accuracy of the proposed method based on speckle vision measurement for the adaptive positioning repair of blades, an adaptive blade positioning and repair experiment was performed. Fig. 7 shows the measurement system platform for adaptive positioning, including DMU-85 moonblock five-axis CNC machining center, computer, control panel, blades, mark points and visual measurement system, where the visual measurement system includes GE500M-T Gigabit CMOS Industrial binocular camera (5.0 Megapixels, resolution 2592 \* 1944, aperture ratio 1: 2.0, focal length \( f = 16 \) mm), bracket, tripod.

The probe of demag five axis machining center should be calibrated before use, so as to make the probe operate within a higher accuracy range. Zhang Zhengyou chessboard is used to calibrate the visual measurement system. The average deviation of the left and right camera internal parameters is 0.06 pixels, which can meet the requirements of this experiment. The internal calibration residuals are shown in Fig. 8 below.
FIGURE 7. Measurement platform for adaptive positioning repair of blade.

FIGURE 8. Residual diagram of internal parameter calibration. (a) Left camera, (b) Right camera.

B. ACQUISITION AND CONFIGURATION OF BLADE CLOUD

Based on the calibration, the visual measurement image is calibrated, and the KLT algorithm is used for the initial matching of speckles. At the same time, the epipolar constraint is used to eliminate mismatches. Under the premise of ensuring observation, select some representative matching points, Fig. 9 (a) is the de-distorted image, and Fig. 9 (b) is the matching image.

Fig. 10 (a) shows the visualization results of the point cloud data in front of the blade with the tenon removed by using the minimum distance objective function method based on the speckle matching. Fig. 10 (b) shows the visualization results of the point cloud data of the rear blade, and Fig. 10 (c) shows the whole point cloud data of the damaged blade spliced based on the mark points.

According to B-spline theory, the point cloud data of the damaged blade is fitted, and the complete model of blade is obtained by surface extension, as shown in Fig.11 (a), (b). Meanwhile, the point cloud fitting deviations of the front and rear blade are shown in Fig. 11 (c), (d).

Through the fitting deviation graph of point cloud, the average deviation of the front blade point cloud is $-0.025$mm, and the standard deviation is $0.114$mm. Meanwhile, the average and standard deviation of the rear blade are $-0.033$mm and
FIGURE 11. (a) Damaged blade model, (b) Complete blade configuration, (c) Fitting deviation of point cloud of front blade, (d) Fitting deviation of point cloud of rear blade.

0.069mm, respectively. The largest deviations appear on the edge of the blade, and the fitting accuracy can meet the application requirement. Therefore, the complete configuration can be obtained by surface extension, which provides a model basis for adaptive positioning and repair of blades later.

C. ADAPTIVE POSITIONING SOLUTION OF THE DAMAGED BLADE

The self-adaptive positioning position and pose of the blade to be repaired in the CNC machining center are calculated. Through the coordinates of the reference mark point and the center point of the probe measured by the visual measurement system, each positioning coordinate system is established, and the space pose between the four positioning coordinate systems is calculated, and the pose matrix of the mark point coordinate system to the machine coordinate system is obtained

\[
\begin{bmatrix}
W_P T \\
\end{bmatrix} =
\begin{bmatrix}
0.9998 & 0.0070 & 0.0022 & 470.7690 \\
0.0007 & 1.0160 & 0.0017 & -434.8930 \\
-0.0022 & -0.0017 & 1.0000 & -479.6474 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

FIGURE 12. (a) Rough machining repair, (b) Semi-finishing machining repair, (c) Finishing machining repair, (d) Milling repair process.

FIGURE 13. Machining simulation of the generated tool path (a) Overall view, (b) Partial view, (c) Simulation completed diagram.

By substituting the position matrix of the mark point coordinate system to the machine coordinate system into (3), the position information of the blade in the machine coordinate system of the five-axis machining center can be calculated, that is, the adaptive positioning of the damaged blade assisted by the visual measurement is realized.

D. GENERATION OF THE REPAIR PATH

Through the above calculation, the adaptive positioning of the laser cladding blade in the CNC machining center is
completed. Then the trajectory planning of the area to be repaired is completed, and the redundant cladding materials at the blade corner are removed. Fig. 12 shows the tool path and repair process of blade adaptive positioning repair.

E. SIMULATION AND MILLING EXPERIMENT

1) VERICUT SIMULATION VERIFICATION

It can visually observe the tool movement process through machining simulation, to check whether the calculation of tool position is correct, whether the machining process has over cutting, whether the selected tool, path of cutting, and mode of approaching and retraction are reasonable, and whether the tool collides with the parts to be repaired and all parts of the machine tool. Vericut machining simulation is carried out for the planned self-adaptive positioning repair path to generate the repair path, complete the real-time simulation processing, and verify the reliability of the tool path, process and algorithm. In the verification process, not only the generated NC code is run, but also the conflicts and interferences are checked, which provides a reference for the actual repair of blades. Fig. 13 shows a simulation of the adaptive positioning milling repair of the blade to be repaired using the vericut simulation software.

2) BLADE REPAIR EXPERIMENT

DMU-85 monoblock machining center was used to carry out milling repair experiments on the repaired blades after laser cladding. The NC code generated was run, and no interference occurred in the experiment, which verified the rationality of generating NC code.

Fig. 14 shows the repairing process of the blade in the CNC machining center. The experiment of self-adaptive positioning and repair using speckle vision measurement has a quite good effect, which verifies the feasibility of the repair method proposed in this paper.

F. ANALYSIS OF RESULTS

For the aero-engine blade repaired by adaptive positioning milling, an accurate and detailed analysis should be carried out to determine the effectiveness of the whole repair process. In the process of blade repair, the inspection is completed by obtaining the size of the blade airfoil. The main indicators of the detection are the blade height, local repair thickness, chord length, and arc length that need to be controlled. ZEISS

TABLE 2. Geometric parameters of repaired blade.

| Parameters       | Intact part (mm) | Repaired part (mm) | Deviation (mm) |
|------------------|------------------|--------------------|----------------|
| Height           | 49.785           | 49.594             | 0.191          |
| Local thickness 1| 3.342            | 3.456              | -0.114         |
| Local thickness 2| 2.978            | 3.115              | -0.137         |
| Chord length     | 45.969           | 45.690             | 0.279          |
| Arc length       | 46.228           | 46.015             | 0.213          |
global bridge-type coordinate measuring instrument (measurement accuracy: 0.001 mm) was used to make contact measurement of the geometric parameters of the intact part and the repair part of the blade, and the deviation was checked. These tolerances may vary due to the blade type and stage of the aero-engine blade. The geometric parameters of the blade after the self-adaptive positioning repair using speckle vision measurement should be within the tolerance range. Table 2 gives the geometric parameters of the repaired aero-engine blade. Fig. 15 shows the cross-section measurement of the blade with CMM. Fig. 16 shows the laser cladding and repaired blades. Fig. 17 is the schematic diagram of point cloud which was measured by CMM and the geometric parameters of key section for contact measurement. It is shown that ten cross-sections were obtained on the region in interest and the other five cross-section were measured on the bottom part of the blade.

VIII. CONCLUSION

An adaptive positioning and repair method for complex curved blades using speckle vision measurement is proposed. The laser cladding damaged blade which is under-positioned clamped in the DMG CNC machining center will be self-adaptive positioned through the speckle vision measurement by the position and orientation calculation of each positioning coordinate system. Therefore, the positioning of traditional artificial exclusive fixture which needs the complex operation of clamping and calibrating many times in the process is avoided. Then the tool path planning of the excess cladding material in the area to be repaired of the blade is performed, and the single-way point-to-point fixed area repair path improves the efficiency of blade repair to a certain extent. Visual measurement and self-adaptive positioning repair experiments were carried out for the damaged blades. After the repair, the geometric parameters of the repaired area were examined to verify the proposed method. The experimental results show that the self-adaptive positioning repair of the damaged engine blade using speckle vision measurement can achieve quite good experimental results under the existing experimental conditions, and can provide a new idea for digital manufacturing and repair of damaged aero-engine blades.

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