CAD-Based Path Planning for 3D Laser Scanning of Complex Surface

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Abstract

A CAD-based approach to plan the laser scanning path of complex surfaces is presented. Firstly, in the laser scanning process the issues of the positional relationship between scanning direction and normal vectors of sampling points of the measured surface, sensor work area check and surface occlusion judgment are researched and a method for generating a single arbitrary surface scanning path is developed. Secondly, through the analysis of surface segmentation, scanning directions and displacements synthesis during the multi-surface scanning process, a scanning path planning method based on any complex multi-curved surface is established. Finally, through a simulation example, the feasibility of the method is verified.

Keywords: CAD model; single arbitrary surface; laser scanning; path planning

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1. Introduction

In recent years, the reverse engineering technology has been more widely applied in the digitization and manufacture of industrial products. It is an essential technology to achieve digital reconstruction of physical geometrical models and remanufacture of products. In the geometric modeling process, the 3D laser scanning technology features high measuring speed, easy operation and acquisition of massive point cloud data. In this process, how to improve the accuracy of laser scanning to obtain accurate point cloud data is one of the key technologies for the subsequent modeling. Up to the present day, some researches have been made on the planning of the laser scanning path. In Literatures 4-5, the scanning angle, field-of-view and depth parameters were analyzed, and a algorithm process of the scanning path for a single arbitrary curved surface was developed based on the CAD model of measured surface; In literature 6, after the area of the measured surface is divided for scanning, the contour of each scanned area was analyzed and the upper and lower boundaries of the scanned surface were defined. Then the sensor position and scanning actions were determined on the basis of the maximum field of view in the scan area. All the scanning actions in each area were correlated to form the final scanning path. In Literature 7 ,with back light, contour images of the object shadow from different angles were obtained, which contribute to the rough surface data of the measured object. The convex hull polygon from the surface data was taken as the scanning path of the line structured light sensor. Next, the measuring viewing angle of the sensor was changed to complete the automatic scanning of the measured object. In Literature 8, the machine parts were scanned by the laser displacement sensor mounted on the CMM. Firstly, the CAD model of the object was gridded and the visibility of each grid patch was analyzed. And then, the optimal view point of the sensor was determined through calculation. Finally, a portion of the viewpoints were linked to shape the scanning path.

According to the analysis on the CAD surface model and the sensor scanning parameters, this paper presents an algorithm for planning the laser scanning path of single CAD surface model and hereby formulates a surface scanning method and process for complex parts.

2. Determination of Effective Surface Scanning Range based on Sensor Scanning Error

Factors affecting the sensor scanning accuracy include: sensor parameters, scanning process parameters and part surface factors, of which, the sensor parameters mainly include: properties and structure parameters of sensor elements; the scanning process parameters refer to the scan path, direction[9-10] and motion parameters; part surface parameters include part material and surface quality. Wherein, the sensor parameters and the scan path play a major role.

![Fig.1. 3-D surface laser scanning](image)

The scanning accuracy of the laser sensor is associated with the position of the sensor relative to the measured surface. Fig.1 shows the case that the sensor scans a surface. In the figure, the scanning direction $R$ is just the direction of Axis $Z$ of the laser sensor, $q_i$ is the normal vector at an arbitrary sampling point $p_i$ on the surface. In the scanning process, the accuracy of the sensor scanning on a point is associated with the angle $\gamma_i$ between $R$ and $q_i$. The angle $\gamma_i$ between the scanning direction of the sensor and the outer normal of the sampled point must be
confined in order to control the accuracy of the sensed data within a certain range, i.e., $\gamma_i \leq \gamma$. $\gamma$ is the predetermined angle threshold to ensure the scanning accuracy. The angle $\gamma_i$ should satisfy the following formula:

$$\gamma_i = \arccos\left(\frac{R \cdot q_i}{|R||q_i|}\right) \leq \gamma$$

As shown in Fig.2, to ensure that the sensor can accurately acquire the data of the measured surface, the angle between the sensor scanning direction and the normal vector at the data point of the measured curved surface should be controlled within the range indicated by the visual cone, wherein, $\gamma$ is also called as the visual cone angle.

We can have an analysis on the CAD model of the surface before starting the actual measurement. And then, divide the CAD surface model into triangular meshes and obtain outer normal vector of each patch. Next, carry out the identification of the effective scanning area by replacing the surface sampling points with the obtained vector, i.e. establishing the retinal cone by taking the scanning direction as the central axis. Determine whether patches contained in this normal vector is in compliance with the undistorted scanning area by observing if the angle between each patch and the scanning direction is within the visual cone.

Finally, after taking the boundary points of triangular patches corresponding to all the normal vectors that can meet the non-distortion requirement, and connecting all the boundary points, the boundary of the effective scanning area is presented.

3. Determination of Surface Scanning Direction and Scanning Displacement

During surface scanning, several scanning directions should be determined so that the scanning range covers the entire surface, and there should be some overlapped areas between every two adjacent surfaces.

The scanning direction can be determined via the following method. Firstly, find the outer normal $n_1$ and $n_2$ of the patches $C_1$ and $C_2$ corresponding to the largest normal vector angle of the surface to be measured, and translate the vector $n_1$ (or $n_2$) to the starting point of the vector $n_2$ (or $n_1$) so that the two vectors intersect with each other. Within the angle plane formed by the two vectors, get the vector $v_1$ (or $v_2$) and make the angle of it with $n_1$ (or $n_2$) be the visual cone $\gamma$, thus the vector $v_1$ (or $v_2$) is namely the initial scanning direction. Next, search the patches which satisfy that the angle between normal vectors of them and the initial scanning direction are smaller
than $\gamma$, with the vectors $v_1$ and $v_2$ as the axis, and find the boundary line of their coverage, which is namely the effective scanning range in this scanning direction (Fig.3).

Finally, repeat the above procedures for the remaining area (including the section overlapped with the area scanned in the previous step) until the surface area is fully covered.

Following the determination of the scanning direction and the effective coverage area, next step is to determine the scanning displacement (Fig.4) of the effective area in each scanning, which can be completed through the steps below:

Step 1: Calculate the effective scanning range in a certain scanning direction on the curved surface $\Omega$, and find the boundary line $\Gamma$.

Step 2: Set up a projection plane $\Sigma$ perpendicular to the scanning direction in order to obtain the projection boundary line $\Gamma'$ of the boundary line $\Gamma$ on this projection plane. Within the projection boundary line $\Gamma'$, establish a rectangular line frame $abcd$ surrounding the projection boundary line $\Sigma$, with the farthest line of projection boundary dot as the long side.

Step 3: Connect the midpoints $e'$ of $ab$ and $cdn$, and find the projection point $e$ (or $f$) of the point $e''$ (or $f''$) on the curved surface $\Omega$. And then, take this point as the base and the distance $\Delta L$ ($\Delta L$ value should ensure that the midpoint value of the sampling point projection in the scanning direction is namely the median of the effective scanning distance of the sensor) in the scanning direction as the length to calculate the value of the point $e'$ (or $f'$). Next, draw a line parallel with the segment $e''f''$ through the point $e'$ (or $f'$), and the parallel line will intersect with the extended line of the segment $f'f$ (or $e'e$) at the point $f''$ (or $e''$), then the vector $e'f''$ is namely the scanning displacement.

Step 4: The length of the segment $ab$ or $cd$ may be considered as the actual scanning width. Suppose the width in a scanning is $\Phi$, if $ab/\Phi = N$, the actual scanning width may be achieved by multi-scanning. Given the overlap between adjacent scanning widths is required, the number of scans should be greater than $N$.

4. Check on the Effectiveness and Occlusion of Scanned Area

4.1. Check on the Effectiveness of Scanned Area

The laser sensor has an field of view (FOV). Only the scanned surface is always located in this area, can the accurate data be acquired. After the effective scanning range and the scanning path are determined, the scanning range should be checked to verify if it is within the FOV of the sensor. Firstly, define the bounding box of the terrace according to the scanning path, and judge whether the boundary point of the scanning range is within the bounding box. The judgment process may be achieved based on the positional relationship between the normal vector from the boundary sampling point of the scanned surface to the boundary planes of the bounding box and the outer normal of the boundary planes of the terrace working area (Fig.5).
Suppose the perpendicular foot from the point \( p \) (the apex of the triangular patches) to the boundary plane \( i \) \((i = 1, \ldots, 6)\) is \( e_i \). Set \( \mathbf{n}_i = e_i p \), and the outer normal of the boundary plane \( i \) is \( \mathbf{n}_i \), if:
\[
\mathbf{n}_i \cdot \mathbf{n}_i < 0 \quad (i = 1, \ldots, 6)
\]
Then we can believe that the point is within the effective range of the bounding box, otherwise it is outside the bounding box.

4.2. Occlusion Check and Processing of the Scanned Surface [11-12]

During the judgment of the triangular patch occlusion, arrange sampling points along the three sides of the triangle, and points for each side (uniformly distributed). And then, respectively draw a line to connect the sampling points of each side and the three apexes of every triangular patch with the two CCD of the sensor. Next, check if the lines are intersected with other triangular patches so as to judge the occlusion issues.

For most of the relatively flat surfaces, the initial scanning path is enough to work. If any occlusion occurs, first check whether the point can be found by scanning in other directions. If not, rotate by a certain angle (Fig. 6) around the x-axis of the sensor. In case the rotation directions of occlusion points conflict with each other, an additional scanning direction should be considered.

5. Generation of Scanning Path on Complex Part Surfaces

The surface of a complex part is often composed of multiple curved surfaces (or planes), so it is quite necessary to establish a number of scanning paths for the acquisition of surface data. Based on the determination of a single surface scanning direction and the calculation of the displacement conducted above, the planning of multiple surface scanning paths for complex parts may be made as follows:
Step 1: Arrange the parts at proper position and angle so that the scanning is easy to achieve. In addition, try to keep the position and angle of the parts unchanged in the entire scanning process.
Step 2: Segmentation of the scanned surface
Step 3: Select the major surfaces. The major surfaces refer to a surface with a large area, or associated with high accuracy.
Step 4: Determine the scanning direction of each surface (ensure that there is partial overlapped area between two consecutive scans). It is necessary to incorporate the similar direction vectors in term of the scanning direction (the maximum angle between the direction vectors is less than a predetermined value) and take the mean value of the similar scan direction vectors as the synthetic scanning direction.

The synthesis of similar scanning directions may be achieved in accordance with the following steps:

1. Set an angle threshold $\varphi$ for the identification of similar vectors.
2. Calculate the angles between any two direction vectors, and find a certain direction vector which, together with other direction vectors, can form the largest number of angles smaller than $\varphi$. And then, incorporate this vector into all the other similar vectors (angles of vectors are smaller than $\varphi$) to form one vector group.
3. Calculate the mean value of this vector group, which will be used as the synthetic scanning direction of the group.
4. Repeat Steps (2) to (3) on the direction vectors of the remaining surfaces until the synthesis of all scanning directions is completed.

Step 5: Perform the calculation related to the work area and occlusion for each scanning direction, and adjust the scanning direction when necessary based on the calculation results.

Step 6: Determine the scanning direction according to Steps 3 to 5, and define the start and end points of scanning displacement in each scanning direction. In this process, the scanning displacements in the same scanning direction should be incorporated as much as possible, i.e. all the relevant scanning areas are covered in this direction by only one scan; in addition, try to achieve the end-to-end connection of the scanning displacements in adjacent scanning directions so that the scanning is continuous.

Step 7: Calculate the effective coverage of the above scanning direction and path. And repeat Steps 4 to 6 for the remaining uncovered measured surfaces to determine their scanning directions and displacements, so that the scanning path for all the measured surfaces is finally generated.

The algorithm to generate the scanning path for the overall surface is shown in Fig. 7.

6. Simulation Examples

Next, we’ll give an explanation of the algorithm presented in this article through its application in the generation process of the scanning path for the outer surface (excluding holes or inner surfaces of the part) of a reducer upper cover. Fig.8 shows the gridded surface model of a reducer upper cover and the coordinate system of the part.
The results of segmentation and numbering the outer surface of the part are shown in Fig. 9 (the figures in brackets are the numbers of the symmetric surfaces). Based on analysis, the major surfaces (numbers) include 1, 2, 3, 4, 5, 6 (7), 8 (9), 12 (13), 14 (15), 34 and 35; and large surfaces (numbers) are: 10 (11), 20 (21).

Set the visual cone angle $\gamma = 45^\circ$ (i.e. the sensor scanning error is less than 5 um) and the final synthetic scanning direction is $(0, 0, -1)$. The same method may be applied to the remaining non-major surfaces, and the final scanning direction as well as the start and end points of scanning displacement were obtained and given in Fig. 10 and Table 1.
### Table 1. List of Scanning Directions, Scanned Surfaces as well as Start and End Points of Scanning Displacements for Part

<table>
<thead>
<tr>
<th>Scanning Direction Vector</th>
<th>Scanned surface</th>
<th>Start Point</th>
<th>End Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) (0.707,0,-0.707)</td>
<td>1*,26,27,4,5</td>
<td>(-162.1,0,194.1)</td>
<td>(-69.4,0,286.9)</td>
</tr>
<tr>
<td>(b) (0,0,1)</td>
<td>1*,2,3*,6,7,12,13,14,15,30-35</td>
<td>(0,0,302)</td>
<td>(223,0,302)</td>
</tr>
<tr>
<td>(c) (-0.707,0,0.707)</td>
<td>3,8,9,24,25</td>
<td>(311.4,2,287.9)</td>
<td>(399.1,2,199.7)</td>
</tr>
<tr>
<td>(d) (0.5,0.866,0)</td>
<td>18*,19*</td>
<td>(375.1,252.6,17)</td>
<td>(320.4,284.2,17)</td>
</tr>
<tr>
<td>(e) (0,-1,0)</td>
<td>11,17*,21,31,33,36*,37*</td>
<td>(169,4,330,35.1)</td>
<td>(5,9,330,35.1)</td>
</tr>
<tr>
<td>(f) (1.0,0)</td>
<td>1*,16*,17*,22,23,36</td>
<td>(-250,52,34.7)</td>
<td>(-250,-52,34.7)</td>
</tr>
<tr>
<td>(g) (0,1.0)</td>
<td>10,16*,20,30,32,36*,37*</td>
<td>(5.9,-330,35.1)</td>
<td>(169.4,-330,35.1)</td>
</tr>
<tr>
<td>(h) (0.5,-0.866,0)</td>
<td>18*,19*</td>
<td>(320.4,-284.2,17)</td>
<td>(357.1,-252.6,17)</td>
</tr>
<tr>
<td>(i) (-1.0,0)</td>
<td>2*,18*,19*,28,29,37</td>
<td>(490.5,-52,31.6)</td>
<td>(490.5,52,31.6)</td>
</tr>
</tbody>
</table>

Note: The numbers marked with (*) in the table means the corresponding surface was only scanned partially.

Fig. 11 shows the finally-generated scanning path of the outer surface. A laser scanning sensor is placed on a CMM. After the reducer upper cover was scanned along this scanning path, the point cloud model of the reducer upper cover was finally formed through point cloud processing and registration (Fig. 12).
Table 2. The error values between sampling points and the corresponding closest points of laser scanning model

<table>
<thead>
<tr>
<th></th>
<th>Maximum deviation</th>
<th>Average deviation</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive value</td>
<td>0.187</td>
<td>0.049</td>
<td>0.036</td>
</tr>
<tr>
<td>Negative value</td>
<td>-0.192</td>
<td>-0.054</td>
<td>0.043</td>
</tr>
</tbody>
</table>

A certain number sampling points uniformly distributed on the part surface are taken, which are contact measured by CMM. Though registering CMM data points and laser scanning point cloud model, the error values between sampling points and the corresponding closest points of laser scanning model can be obtained. The error values are showed in Table 2.

7. Conclusion

The error-generating factors in the laser scanning process was analyzed, and the principle and method for planning the laser scanning path of complex surface based on the CAD model were presented in this article.

With the wide application of the laser scanning technology in reverse engineering and error detection fields, the requirement on the point cloud modeling accuracy is increasingly high. In this case, the design and manufacture of the laser scanning sensor itself is urgently needed to be improved. In addition, the method to generate and optimize the scanning path of complex surfaces is an important issue for further development of this field.

References

