Path Planning for Surface Inspection on a Robot-Based Scanning System

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Abstract - This paper proposes an automatic model-based path planning method for surfaces inspection on a robot-based scanning system. The original CAD model of the surface is a triangular mesh model. The scanning system consists of a 6 degree of freedom robot and a coded structured light scanner. Based on the system structure and the working conditions of the scanner, some scan constraints, i.e. field of view, working distance, view angle, and overlap, are concerned in path planning. The proposed method consists of four steps: model framework extraction, scan region segmentation, viewpoint generation, and scan path generation. Firstly, model framework is extracted from the projection of model in main direction. Secondly, the model is divided into several scan regions based on the framework. Thirdly, viewpoints satisfied scan constraints are planned for each scan region. Lastly, a scanning path is generated passing through these viewpoints. Experiments are presented to demonstrate the feasibility and advantages of the proposed method.


I. INTRODUCTION

Nowadays, structured light based surface measurement technique has been wildly used in surface inspection, reverse engineering, cultural heritage, medicines, etc [1-4]. Compared with the Coordinate Measurement Machine (CMM), a typical contact-type surface measuring device, the structured light scanner is non-invasive, faster, and much less expensive [5]. Particularly, the newly developed coded structured light scanner has notably improved the scanning efficiency by replacing line scanning mode, which is applied in the line structured light scanner, with plane scanning mode. Therefore, the coded structured light has been used more and more widely in surface inspection. However, a scanner can only detect a portion of the object from a single viewpoint, when the object has large surface. Therefore, a moving platform is usually required to move the scanner or the object in an automatic scanning system. The scanning system studied in this paper consists of an industrial robot with 6 degree of freedom (DOF) and a coded structured light scanner. The scanner is mounted on the end of the robot.

Since multiple viewpoints are often required for an object scanning, path planning which generates scan viewpoints and a path through these viewpoints are critically important for full automatic and high efficient inspection. Usually, surface inspection is a model-based issue, where the CAD model of the scanned object is assumed to be known. In this paper, the surface model is given as a triangular mesh model for its advantages of simplicity and robustness.

Many previous research works on scanning path planning are related to other scanning devices, such as CMMs, laser scanners, and cameras. Lee et al. [6-8] proposed an automated path planning method for freeform shape part inspection using laser scanners. Five constraints were concerned in the method: view angle, field of view (FOV), depth of view, beam occlusion-free, and path occlusion-free. Elkott et al. [9] developed a sampling method based on genetic algorithm for freeform surface inspection planning using CMMs. Chen et al. [10] proposed an automatic viewpoint planning method for robot vision system, which is equipped with stereo vision sensors. All geometrical, optical, reconstructive, and environmental constraints were considered in this research. Fernandez et al. [11] developed an automatic viewpoint planning system for 3D surfaces scanning using a laser stripe system mounted on a CMM. Both laser system and CMM system constraints had been considered. Martinez et al. [12] developed a sensor planning system for headlamp lens inspection using cameras, considering constraints of visibility, FOV, resolution, focus, and view angle. Scott [13] proposed a modified measurability matrix path planning algorithm for object inspection with laser scanners. Zhou et al. [14] presented a search-based path planning method for freeform surface inspection. Zhao et al. [15] developed a path planning method for multi-sensor system, where a laser line scanner is combined with a touch trigger probe.

This paper proposes an automatic model-based path planning method that can achieve high precision and efficiency for surface inspection on a robot-based scanning system. The planned path is linked by a group of viewpoints, from which the scanner can detect the full features of the object. In order to achieve high-precision measurement, each viewpoint should satisfy several scan constraints, i.e. FOV, working distance, view angle, and overlap. The proposed method is mainly composed by four steps: model framework extraction, scan region segmentation, viewpoint generation, and scanning path generation. Firstly, model framework is extracted through projection in main direction of the model. Secondly, the model is divided into several scan regions based on the framework. Thirdly, viewpoints satisfied scan constraints are planned for each scan region. Lastly, a scanning path is generated passing through these viewpoints. An airplane wing model is taken as an example in this paper. Experiment results demonstrate the feasibility and advantages of the proposed method.
II. SYSTEM DESCRIPTION

The scanning system studied in this paper consists of a 6 DOF robot and a coded structured light scanner, as shown in Fig. 1. The scanner is mounted on the end of the robot. The followed four coordinate systems, i.e. robot base coordinate system, robot end coordinate system, scanner coordinate system, and object coordinate system, are established in the scanning system, as Fig. 2 shown.

The scanning path is defined as the path of the robot end, since it can be set by the robot controller easily. Denote $SP$ as the scanning path.

$$ SP : \{ sp_i : \{ ^b R_{EI}, ^b T_{EI} \} | i = 1, \ldots, N_{VP} \} $$

where $sp_i$ is a path point, $^b R_{EI}$ and $^b T_{EI}$ are the rotation matrix and the position vector of the robot end in robot base coordinate system respectively, when the robot end is set at the path point $sp_i$.

In the scanning path, the scanner will pass though these viewpoints. According to the system structure, the relationship between $VP$ and $SP$ is as follows

$$ \begin{bmatrix} ^b R_E, ^b T_E \end{bmatrix} = \begin{bmatrix} ^b R_o, ^b T_o \end{bmatrix} \begin{bmatrix} S^o R_s, S^o T_s \end{bmatrix} \begin{bmatrix} ^o R_s, ^o T_s \end{bmatrix} \begin{bmatrix} ^o R_s, ^o T_s \end{bmatrix}^{-1} $$

(1)

where $\{ ^o R_o, ^o T_o \}$ is the pose and position of the object in the robot base coordinate system, $\{ ^o R_s, ^o T_s \}$ is the pose and position of the scanner in the robot end coordinate system.

III. SCAN CONSTRAINTS

Some scan constraints should be considered during path planning process. Firstly, the measured points should be within the working distance of the scanner. Secondly, the measured points should be located within the FOV of the scanner. Thirdly, overlap area is required for integrating data detected from different viewpoints. The followed parameters are related about above scan constraints:

1. Working distance range: $[H, H+h]$;
2. Smallest range of FOV: $l_1 \times w_1$;
3. Largest range of FOV: $l_2 \times w_2$;
4. Maximum acceptable view angle: $\theta_T$;
5. Minimum acceptable width of overlap $W_f$.

In this paper, the CAD model is a triangular mesh model. As shown in Fig. 3, $f$ is a triangular facet within the measured location of the scanner. Suppose $v_1, v_2, v_3$ are three vertexes of $f$, $v_C$ is its centroid, and $n_f$ is its normal vector. If the coordinates of $v_1, v_2, v_3$ in the scanner coordinate system are denoted as $(\delta x_1, \delta y_1, \delta z_1)$, $(\delta x_2, \delta y_2, \delta z_2)$, and $(\delta x_3, \delta y_3, \delta z_3)$ respectively, the coordinate of $v_C$ can be calculated as:
In summary, the constraints are given as follows:

1. Working distance: the three vertexes should be within the working distance range, as Fig. 3 shown.
   \[
   H \leq \frac{s_z}{H + h} \leq H + h
   \]
   \[
   H \leq \frac{s_z}{H + h} \leq H + h
   \]

2. FOV: the three vertexes should be located within FOV, as Fig. 3 shown.
   \[
   \begin{align*}
   \frac{s_z}{2H} \leq \frac{w_i}{2H} \leq \frac{s_z}{2H} \\
   \frac{s_z}{2H} \leq \frac{w_i}{2H} \leq \frac{s_z}{2H} \\
   \frac{s_z}{2H} \leq \frac{w_i}{2H} \leq \frac{s_z}{2H}
   \end{align*}
   \]

3. View angle: The angle between negative unit vector of scan direction \( s_D \) and \( n_v \) should be less than \( \theta_T \), as shown in Fig. 3.
   \[
   -s_p \cdot n_v \geq \cos \theta_T
   \]

4. Overlap: the width of overlap is larger than \( W_v \), as shown in Fig. 4.

IV. PATH PLANNING METHOD

The data of triangular mesh model \( F \) consists of vertexes and normal vectors of facets.

\[ F = \{ f_i : \{ v_{i1}, v_{i2}, v_{i3}, n_{i} \} \mid i = 1, \cdots, N_F \} \]

Define a \( 1 \times N_F \) array \( M \) to record the statuses of facets.

\[
M(i) = \begin{cases} 1; & \text{if } f_i \text{ has been planned} \\ 0; & \text{otherwise} \end{cases}
\]

The overall procedure of the proposed method consists of four steps: model framework extraction, scan region segmentation, viewpoint generation, and path generation, as shown in Fig. 5.

A. Model Framework Extraction

In this step, model framework is extracted through model projection in the main direction \( n_m \), which is determined by the global mean of the normal vectors in the model.

\[
\bar{n}_m = \frac{\sum_{i=1}^{N_F} n_{ig}}{\sum_{i=1}^{N_F} n_{ig}}
\]

All the vertexes in the model are perpendicularly projected on to plane \( \Pi \), which passes through the origin \( O_o \) and has the normal vector \( n_m \), as shown in Fig. 6. The projected points \( p_i \) of a vertex \( v_i \) is calculated as

\[
p_i = v_i + (v_i \cdot n_m) n_m
\]
the framework is generated by rotation method [16]. MER is defined as

$$\text{MER} : I_{\text{MER}} \times w_{\text{MER}}$$  \hspace{1cm} (9)$$

where

$$S_{\text{MER}} = I_{\text{MER}} \times w_{\text{MER}}$$

$$= \min S_{\text{rec}}$$

$$PF \subset S_{\text{rec}}$$  \hspace{1cm} (10)$$

$$= \min(I_{\text{rec}} \times w_{\text{rec}})$$.

B. Scan Region Segmentation

In this step, the model is divided into several scan regions based on the framework. Taking the smallest range of FOV and overlap constraint into consideration, a rectangle $R_i$ with the size of $(l_i - W_i / 2) \times (w_i - W_i / 2)$ is set as the basic unit of framework segmentation. The segmentation of framework is as shown in Fig. 8. The framework is divided into $N_S$ portions.

$$N_S = \text{ceil} \left( \frac{l_i}{l_i - W_i / 2} \right) \times \text{ceil} \left( \frac{w_{\text{MER}}}{w_i - W_i / 2} \right)$$  \hspace{1cm} (11)$$

where $\text{ceil}()$ is a round up function to an integer. Denote $F_j$ as a scan region. $F_j$ is defined as

$$F_j : \{ f_j | \text{p}_{cj} \in R_j \}$$  \hspace{1cm} (12)$$

where $\text{p}_{cj}$ is the projection of $f_j$’s centroid.

C. Viewpoint Generation

In this step, viewpoints satisfied scan constraints are planned for each scan region. The scan direction $s_D$ is determined by the global mean of the normal vectors in $F_j$.

$$s_D = \frac{\sum_{f_j \in S} n_{sk}}{\sum_{f_j \in S} n_{sk}}$$  \hspace{1cm} (13)$$

All the vertexes in $F_j$ are perpendicularly projected onto plane $\Pi_j$, which passes through the origin $O_j$ and has the normal vector $s_D$. The projected point $p_j$ of a vertex $v_i$ is calculated as

$$p_j = v_i + (v_i \cdot s_D) s_D$$  \hspace{1cm} (14)$$

Then, MER of the projections is generated by rotation method. Denote $M_j$ as the MER, $P_{RC}$ as the centroid of $M_j$, $P_{R1}$, $P_{R2}$, $P_{R3}$, $P_{R4}$ as the four vertexes of $M_j$, as Fig. 9 shown. Thus, the rotation matrix of this viewpoint is given as

$$\alpha_{\text{R}_s} = \begin{bmatrix} P_{R1} & P_{R2} \\ P_{R3} & P_{R4} \end{bmatrix}$$  \hspace{1cm} (15)$$

Taking overlap constraint into account, the FOV range of this viewpoint is set as

$$\text{FOV} : \left[ P_{R1} + \frac{W_r}{2} \right] \times \left[ P_{R1} + \frac{W_r}{2} \right]$$

According to the relationship between the working distance and FOV range of the scanner, the working distance $d_j$ of this viewpoint is given as

$$d_j = \max \left( \frac{P_{R1} + P_{R2} + W_r}{2}, \frac{P_{R1} + P_{R2} + W_r}{2} \right)$$  \hspace{1cm} (16)$$

All vertexes in $F_j$ are perpendicularly projected onto line $L$, which passes through $P_{RC}$ and is parallel to $s_D$, as shown in Fig. 9. The projected point $p^i_j$ of a vertex $v_i$ is calculated as

$$p^i_j = P_{RC} - (v_i \cdot P_{RC} \cdot s_D) s_D$$  \hspace{1cm} (17)$$

Denote $PA^i$ as the set of all projected points. Then the top projected point $P^i_{\text{top}}$ in $PA^i$ can be searched as

$$P_{RC} - p_{\text{top}}^i = \min_{v_i, v_j} P_{RC} - P^i_{\text{top}} \cdot s_D$$  \hspace{1cm} (18)$$

Then, the position of viewpoint is calculated as:

$$\alpha_{\text{T}_s} = p^i_{\text{top}} - d_j \cdot s_D$$  \hspace{1cm} (19)$$

So far, the viewpoint for scan region $F_j$ has been generated.

Lastly, the view angle constraint is utilized to determine the final scan region $F_j'$ of the current viewpoint. All the facets in $F_j$ are checked by the view angle constraint in accordance with (5). Then, $F_j'$ is given as
\[ F'_j = \bigcup_{x_n \in \mathbb{R}^2 \setminus \mathcal{D}_v \cup \bigcup_{i \in \mathcal{D}_v} f'_i; f'_i \in F_j } \]

Mark all facets in \( F'_j \)

\[ M(i) = 1 \text{ if } f'_i \in F'_j \]

When the viewpoint set \( VP \) is generated by the previous steps, the scanning path \( SP \) passing through these viewpoints can be generated by (1).

V. EXPERIMENTS

The proposed method was tested through an airplane wing surface. The surface model was shown in Fig. 10, which contained 14823 facets. The specification of scan constraints was given in Table I. The path planning method was implemented in MATLAB.

![Fig. 10 Triangular mesh model of airplane wing surface](image)

**Table I Scan constraints**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smallest range of FOV</td>
<td>300 mm ( \times ) 240 mm</td>
</tr>
<tr>
<td>Largest range of FOV</td>
<td>480 mm ( \times ) 380 mm</td>
</tr>
<tr>
<td>Working distance range</td>
<td>0.5 m ( \text{–} ) 0.8 m</td>
</tr>
<tr>
<td>Maximum acceptable view angle</td>
<td>45°</td>
</tr>
<tr>
<td>Minimum acceptable width of overlap</td>
<td>40 mm</td>
</tr>
</tbody>
</table>

The model framework was extracted as shown in Fig. 11. The black polygon represented the model framework. The blue rectangle represented MER. The green lines indicated the region segmentation. Thus, the model was divided into 18 regions. However, some region contained none facets.

Through viewpoints generation step, a viewpoint set including 13 viewpoints was obtained. The viewpoints and scan regions were shown in Fig. 12. Then, a scanning path was generated by (1). The planned path was adopted by the robot-based scanning system for an airplane wing inspection, as shown in Fig. 13. The scanned model of the airplane wing was shown in Fig. 14.

The software Geomagic was adopted to calculate the difference between the scanned model and the CAD model. The interface of software was shown in Fig. 15. The calculation results were shown in Fig. 16. The maximum difference was 15.1 mm, the standard difference was 3.7 mm.

![Fig. 11 Framework extraction](image)

![Fig. 12 Framework extraction](image)

![Fig. 13 Surface scanning system](image)
enables that the proposed method can be applied to any shape of objects. The four constraints, i.e., FOV, working distance, view angle, and overlap, are considered to guarantee the effectiveness of the planned viewpoints. An airplane wing is taken as an example in this paper. A scanning path for the airplane wing surface is planned by the proposed method. The experiment results demonstrate that the robot-based scanning system detects all feature of the airplane wing through the planned path.

REFERENCES


V. CONCLUSIONS

This paper proposed an automatic model-based path planning for surfaces inspection based on the robot-based scanning system. The utilization of triangular mesh model