View planning method for sheet metal parts in automated 3D measurement

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The automated 3D measurement system, utilizing structured light technology and robotics, is extensively employed in the inspection of sheet metal parts. This system provides essential data for process optimization and enhances part quality. To facilitate automated inspection, it is imperative to pre-plan the measurement viewpoints and paths. However, traditional methods, which sequentially address the planning of measurement viewpoints and paths, often fall into local optimization, thereby reducing measurement efficiency. Moreover, the highly reflective properties of sheet metal surfaces often cause image underexposure or overexposure, leading to discrepancies between actual measurements and simulations. To address these challenges, this paper presents a novel view planning method for highly reflective sheet metal parts. By leveraging the Blinn-Phong model to analyze the interaction between structured light projection and surface reflectivity, the proposed method ensures the consistency of actual measurements with simulations. Furthermore, a random key genetic algorithm is introduced to optimize the viewpoints, which can generate the best measurement viewpoints and paths simultaneously, improving the measurement efficiency. Experiment results demonstrate that the measurement coverage rate achieved by this method is nearly identical to the predicted result (97.4% vs. 98.8%), and there is a 10% increase in efficiency compared to the traditional methods.

Keywords: Sheet metal parts; View planning; Structured light; Reflection model; Genetic algorithm.

1. Introduction

The automated three-dimensional (3D) measurement system, utilizing the structured light technology and robotics, has been widely applied in the inspection of sheet metal parts. To facilitate automated inspection, it is imperative to pre-plan the measurement viewpoints and paths, which aims to realize the required coverage rate with the least movement cost. Most current research sequentially address the planning of measurement viewpoints and paths, which tend to fall into local optimization, making it challenging to acquire complete data and minimize the measurement time simultaneously [1,2]. In addition, the traditional methods neglect the strong reflective properties of sheet metal surfaces (which usually lead to overexposed or underexposed images), resulting in the discrepancy between actual measurements and simulations. Such discrepancy makes it difficult to directly apply the

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planning results to the actual measurement of sheet metal parts [3]. Hence, it is necessary to develop a view planning method suitable for the highly reflective sheet metal parts.

A new view planning method for highly reflective sheet metal parts is proposed in this paper. First, the candidate viewpoints are generated randomly. Then, a reflection model based on the Blinn-Phong model is established to evaluate the measurability of highly reflective surfaces. Finally, the global optimal measurement viewpoints and paths are solved using a random key genetic algorithm, achieving the required coverage rate of the sheet metal surface with the least movement cost.

2. Method

2.1. *Method for Generating Viewpoints for Highly Reflective Sheet Metal Parts*

In this section, a structured light projection-sheet metal surface reflection model based on the Blinn-Phong model is established to ensure the consistency between actual measurements and simulations. The object to be measured in this study is expressed by the triangular mesh method. First, candidate viewpoints are generated around the object randomly, the direction of which are calculated by the potential field method. After that, the visibility of candidate viewpoints is determined based on constraints such as depth of field, field of view, and occlusion constraints. Then, the Blinn-Phong model is used to analyze the measurability at each viewpoint. The Blinn-Phong model is the simplest reflection model, which describes the absorption and reflection of the light on an object's surface by straightforward mathematical principles; and it closely approximates to the actual reflection characteristics of a surface while maintaining relatively low computational complexity [4]. The expression of the Blinn-Phong model is shown as Eq. (1).

$$I = k_a I_a + k_d (\mathbf{L} \cdot \mathbf{N}) I_d + k_s (\mathbf{H} \cdot \mathbf{N})^r I_s \tag{1}$$

where k_a, k_d and k_s represent the ambient reflection coefficient, diffuse reflection coefficient, and specular reflection coefficient, respectively, and $k_d + k_s = 1$; I_a is the ambient light intensity; I_d is the reflected light intensity when the incident light is along the surface normal; I_s is the intensity of the reflected light in the specular reflection direction; $\mathbf{L}$ is the direction of the incident light; N is the surface normal; $\mathbf{V}$ is the viewing direction; $\mathbf{H}$ is the halfway vector, obtained by the average normalization of $\mathbf{L}$ and $\mathbf{V}$; r is the shininess factor, with a larger r indicating a smoother surface.

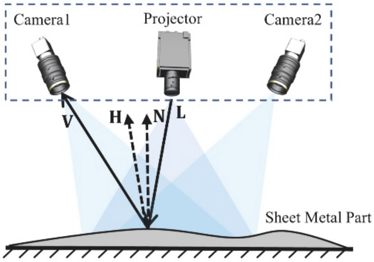


Fig. 1. The structured light projection-sheet metal surface reflection model based on the Blinn-Phong model.

The reflection model between the projection light and the surface of the sheet metal is established based on the Blinn-Phong model, as shown in Figure 1. According to Eq. (1), the reflection coefficient of all surface patches from the current viewpoint can be calculated. After that, the optimal exposure time sequence can be determined by the multiple exposure principle [5]. Then, the actual measurement range of the camera image at each viewpoint can be predicted through single optimal exposure. When the grayscale value of the center of a visible surface patch at a given viewpoint is at the range of 30 to 220, the patch is considered measurable; otherwise, it is not measurable. Thus, the actual measurable area of the sheet metal part from the current viewpoint can be predicted more accurately.

2.2. *View Planning Method Based on Random Key Genetic Algorithm*

The measurement view planning problem, that is, to minimize the total measurement time cost while satisfying coverage constraints, can be expressed as Eq. (2) and Eq. (3).

$$C = \sum_{v_i \in \mathbf{V}} t_i + \sum_{i=1}^{n-1} e(v_i, v_{i+1}) + e(v_h, v_1) \tag{2}$$

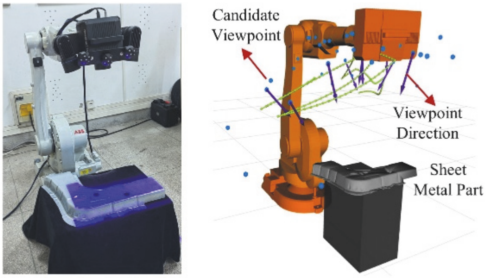
$$\sum_{i=1}^{n} \left(\left(\sum_{j \in \mathbf{V}} \mathbf{M}_j \right) \geq 1 \right) \geq \sigma * n_s \tag{3}$$

where C represents the total measurement cost, $\mathbf{V}$ is the generated ordered set of viewpoints, and n is the number of viewpoints in the set $\mathbf{V}$; t_i is the measurement time at the i -th viewpoint, $e(v_i, v_{i+1})$ is the movement cost between viewpoints v_i an v_{i+1} , and $e(v_h, v_1)$ is the movement cost for the industrial robot to move from the predefined starting point v_h to the first viewpoint v_1; $\mathbf{M}_j$ is the j -th row of the visibility matrix, requiring that each surface patch is covered by at least one viewpoint; σ is the preset coverage rate, and n_s is the total number of triangular surface patches in the target model.

In this section, the Random Key Genetic Algorithm (RKGA), which performs well in global searching and can effectively avoid the issue of premature convergence [6], is adopted to solve the measurement view planning problem expressed as Eq. (2) and Eq. (3). Firstly, an initial a set of viewpoints that satisfies the coverage requirements is randomly selected as individuals to generate the initial population. Secondly, the fitness function based on Eq. (3) is constructed to evaluate the individuals in the population. Thirdly, according to the fitness value, elite individuals are selected to be directly inherited to the next generation; and by crossing and mutating the individuals in the population of current generation, the new generation population can be obtained. Then, the genetic operation (directly inherit, crossing and mutating) is iterated until the pre-set evolutionary algebra is reached. Finally, the individuals in the final generation population are sort in ascending order of their fitness values, and the individual with the smallest fitness value is considered as the optimal result for measurement planning, which is the optimal measurement viewpoint set that satisfies the coverage constraint and with the lowest measurement cost.

3. Experiment

A car's right front inner beam (Sheet Metal Part 1, 400 mm × 500 mm × 60 mm) is used to verify the effectiveness of the proposed method. The coverage requirement is set as 98%. The experimental system consists of an industrial robot (model: IRB1600) equipped with a structured light measurement system, as shown in Figure 2. The measurement system is composed of two industrial cameras (model: BFLY-U3-23S6M-C) and a projector (model: DLP4500).



(a) (b)

Fig. 2. Measurement scene diagram: (a) real measurement scene, (b) viewpoint set generated in a virtual scene.

3.1. *Verification of Measurement Efficiency*

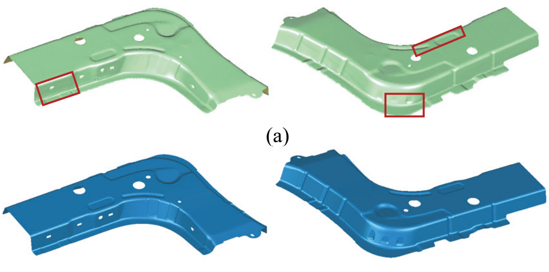
The measurement efficiency of the proposed method is verified in this subsection. The traditional method and RKGA method were used to perform view planning for Sheet Metal Part 1 at 10 times. The total time cost was evaluated, and their average performance comparison is shown in Table 1. It can be seen that in terms of total time cost, compared to the traditional method, the time cost of the RKGA method is reduced by 10.7%.

Table 1. Average Performance for Automated 3D Measurement of Sheet Metal Parts

Experimental Object	View Planning Method	Total Time cost/s
Sheet Metal Part 1	RKGA	88.5
Sheet Metal Part 1	Traditional method	99.1

3.2. *Verification of Measurement Completeness*

The measurement completeness of the proposed method is verified in this subsection. The optimal view planning result of Sheet Metal Part 1 generated by this method includes 9 viewpoints, with a predicted coverage rate of 98.8% in the simulation environment, and the total time cost for automated 3D measurement is 87.2 seconds. The reconstruction result is shown in Figure 3 (a) and the CAD model is shown in Figure 3 (b). The calculated actual surface coverage rate is 97.4% for the Sheet Metal Part 1. From Figure 3, the reconstructed surfaces are smooth and flat, with no significant point cloud omissions, indicating a well performance in the measurement data completeness. However, the actual coverage rate of Sheet Metal Part 1 is slightly lower. Because it contains more surface features, including numerous arc grooves and raised platforms, which are prone to occlusion during measurement, making it difficult to reconstruct these groove bottoms and recessed corners, resulting in slightly data loss.


(a)

(b)

Fig. 3. The Sheet Metal Part 1: (a) the reconstruction result, (b) the CAD model.

4. Conclusion

In this paper, a new view planning method is proposed to improve the efficiency of automated 3D measurement for highly reflective sheet metal parts. By leveraging the Blinn-Phong model to analyze the interaction between structured light projection and surface reflectivity, the consistency of actual measurements with simulations is guaranteed. Furthermore, the RKGA is used to generate the best measurement viewpoints and paths simultaneously, improving the measurement efficiency. Experiments show that the actual measurement coverage obtained by this method is nearly consistent with the predicted results (97.4% vs. 98.8%), and the measurement efficiency is approximately 10% higher compared to traditional distributed planning methods.

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