Application of Phase Measurement Deflectometry Method in Transparent High-Reflection Materials

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Transparent and high inverse material objects have special physical and optical properties, and are widely used I n many fields such as optics, automotive, aerospace, etc., and it is very important to ensure the surface shape accuracy. As a deflection measurement method based on the principle of vision, phase measurement deflectometry (PMD) is widely used in the measurement of highly reflective surfaces, and has advantages in measuring transparent high reflection materials. However, due to the multi-layer reflective surface of transparent and highly reflective material, the image collected by the traditional PMD method often has the phenomenon of signal aliasing, which will affect the accuracy of measurement. For this reason, we propose a new P method for transparent high inverse materials, and propose a method based on dynamic flat mirror calibration and reflective target calibration for this large field of view measurement system. This measurement method discretized the characteristic fringes, and used a single frame phase resolution method to obtain the phase information, and used a binocular camera to shoot one image respectively to complete the surface shape measurement of the transparent high-inverse material surface, which has the advantages of high measurement accuracy and fast speed, and is suitable for transparent high-inverse materials with uniform thickness and moderate curvature as well as ordinary high-inverse surfaces.

NOMENCLATURE

A_i, B_i, C_i, D_i = the coordinates of the feature points pasted on the surface
$\mathbf{n}_i$ = the normal vector of the group i plane mirror
d_i = the distance between the group i plane mirror and the origin of the coordinates
h = the thickness of the reflective mark points pasted
z_c = the homogeneous coefficient
P_c, I_c = pixel coordinate and internal parameter of the camera
R_c, T_c = the binocular rotation and translation matrix
P_s = the coordinate of the screen's point
I, R, T = the identity, screen rotation, and translation matrix
P_{cl0}, P_{cr0} = the pixel coordinates of the screen points mapped in the CCD of the camera by the phase solution calculation.

1. Introduction

Transparent and highly reflective materials are widely used in many fields such as optics, architecture, and transportation because of their special physical and optical properties. Such parts often need to ensure a certain surface shape accuracy before being put into use. For example, the surface shape error of automobile glass will cause an increase in wind resistance, reduce strength, and bring safety risks [1].

To ensure the manufacturing accuracy of transparent and highly reflective materials, high-precision measurement is often an essential step. The commonly used measurement methods for transparent and highly reflective materials currently include scanning measurement and non-scanning measurement. Scanning measurement mainly involves a coordinate measuring machine (CMM) [2]. However, due to the point-by-point contact with the surface of the object being measured during the measurement process, it is easy to cause irreparable damage to the object and has low measurement efficiency. Spraying powder on the surface of the object to be tested changes its transparency and high reflectivity. Using the principle of diffuse reflection and phase projection measurement [3] is also a common measurement method. Grating projection measurement, as a surface measurement method, and has the characteristic of high measurement efficiency. However, due to the powder spraying process on the surface of the object to be tested, measurement errors are caused. PMD [4] as a measurement method based on the principle of reflection, has advantages in measuring transparent and highly reflective materials without changing the surface characteristics of the object being measured. It has the characteristics of high measurement efficiency and accuracy. However, due to the reflective properties of both the upper and lower surfaces of transparent materials, there is a ghosting effect in the collected images during measurement, which brings errors to the measurement results. The method of projecting discrete stripes multiple times [5], but this method requires an increase in the number of captured images, resulting in a decrease in measurement speed. Another approach is to project images of different frequencies to eliminate parasitic reflections from an algorithmic perspective [6]. However, this method also relies on projecting additional images and has high algorithm complexity and long processing time.

Therefore, a discrete measurement method based on transparent high inverse material is proposed in this study. The upper and lower surfaces of transparent objects can be separated according to the brightness and position of discrete fringes by displaying a single frame on the screen, and the surface shape of transparent and high-reflective materials can be restored based on a single frame image. In addition, a method based on dynamic flat mirror calibration and reflective target calibration is proposed to achieve high-precision calibration of the measuring system and high-precision reconstruction of the automotive glass surface.

2. Method

2.1 Measurement Principle

The measurement principle is shown in Fig 1, and Fig.1(a) is the principle diagram of the measurement system. Specific discrete fringes shown on the screen are shown in Fig 1(b). When the transparent or reflective surface to be measured is placed in the measurement area, the feature fringe pattern is captured by the camera under the reflection of the surface to be measured. The captured images are shown in Fig. 1(c). The fringes will be deformed to a certain extent under the modulation of the surface shape of the surface to be measured. The upper and lower surfaces will reflect the fringes, so the images captured by the camera contain obvious double shadows, and the corresponding brightness of the fringes on the lower surface is slightly lower than that on the upper surface. By extracting the upper surface reflection information from the modulated discrete fringe information captured by the camera and calibrating the measurement system, the surface shape of the measured surface can be solved in reverse.

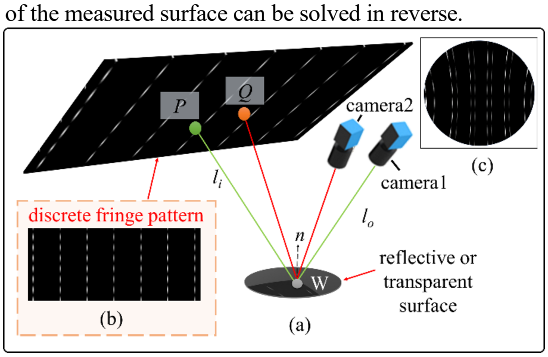

Fig 1 (a) Schematic diagram of the measurement system (b) fringe diagram of discrete features displayed on the screen (c) images captured by the camera

2.2 Calibration Principle

Currently, the commonly used system calibration methods include the traditional dynamic flat mirror calibration method [8] and the reflective target calibration method [9]. In this method, with the increase in system size, screen flatness measurement errors and feature point coordinate measurement errors tend to increase, and these errors will in turn affect the calibration accuracy of screen pose. Therefore, in terms of screen pose calibration, this study combined the traditional dynamic flat mirror calibration method and reflective target calibration method. A dynamic flat-mirror calibration method with features is proposed. The specific idea is shown in Fig 2.

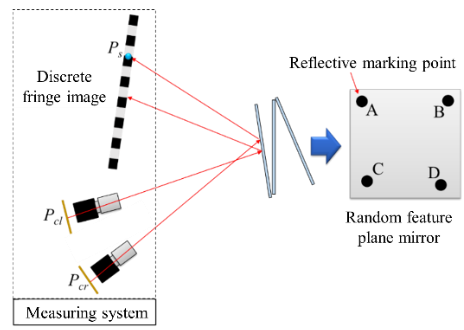

Fig. 2 Schematic diagram of calibration principle

Firstly, binocular calibration is completed based on Zhang's calibration method [7], and then several reflective markers are randomly pasted on the standard flat mirror. Based on the binocular vision principle, the coordinates of the feature points attached to the plane mirror can be calculated, and then the surface shape equation corresponding to the position of the plane mirror can be calculated:

$$\begin{bmatrix} A_i \\ B_i \\ C_i \\ D_i \end{bmatrix} \mathbf{n_i} = d_i + h \tag{1}$$

By combining the camera imaging model and the plane mirror imaging matrix, the mapping equation between left and right camera pixels and screen pixels can be obtained:

$$\begin{cases} z_{cl} P_{cl} = I_{cl} \left[(I - 2\mathbf{nn}^T) R P_s + (I - 2\mathbf{nn}^T) T + 2d\mathbf{n} \right] \\ z_{cr} P_{cr} = I_{cr} \left\{ R_c \left[(I - 2\mathbf{nn}^T) R P_s + (I - 2\mathbf{nn}^T) T + 2d\mathbf{n} \right] + T_c \right\} \end{cases} \tag{2}$$

R can be calculated by the screen rotation angles *thetaxs*, *thetays*, *thetazs*. The optimal equation can be constructed by (t_x, t_y, t_z):

$$\min_{[thetax, thetay, thetaz, tx, ty, tz]} = \frac{\left(p_{cl} - p_{cl0}\right)^2 + \left(p_{cr} - p_{cr0}\right)^2}{2} \tag{3}$$

The formula is the same as the constraint equation of the reflective calibration method, and the initial position of the screen can be obtained through this formula. On this basis, the screen image taken several times in the flat mirror and the constraint of the reflective mark point affixed to the flat mirror are introduced to further improve the calibration accuracy and realize the combination of the reflective target calibration method and the moving flat mirror calibration method. Through the optimization described in the formula, the position and pose of the multi-plane mirror are optimized, and the orientation of the plane mirror is also appropriately constrained, which improves the robustness of the optimization convergence and the anti-interference ability of the screen calibration.

3. Experiment

3.1 System Construction

To verify the feasibility of the method proposed in this paper, a measurement system was built, as shown in Fig 3. The system consisted of two cameras and a large screen, which was used to generate a single fringe pattern to simulate the fringe pattern of discrete features and to facilitate switching the fringe features of appropriate width during the experiment. The camera and screen parameters are shown in Table 1. To improve the positioning accuracy of discrete feature fringes and the calibration accuracy of the system, a 25 million high-resolution camera is selected. Since the system only needs to shoot a single image to complete the measurement, it is not necessary to consider the impact of data transmission of the high-resolution camera on the measurement speed. To verify the practicability of the proposed method for industrial transparent surface measurement, a 400 mm automobile windshield is selected for the specific structure to be measured.

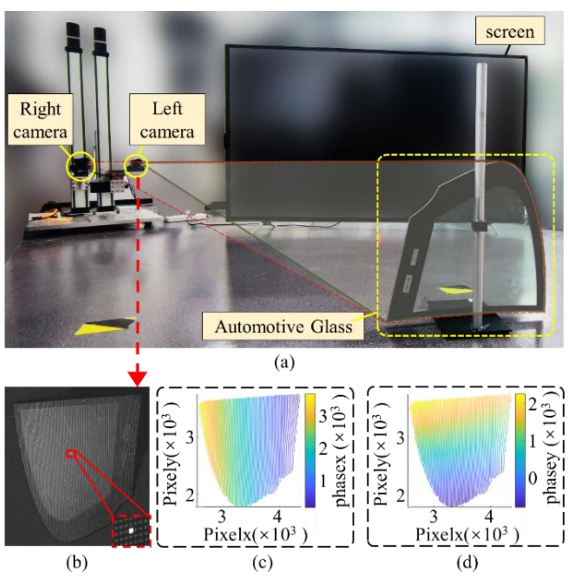

Fig. 3 Measurement system diagram (a) measurement system (b) the image of automobile glass (c), (d) the results of discrete phase solution collected by the measurement system

Table 1 Parameters of each system component

Hardware specification	parameter
Camera	25 million resolution
Lens	25mm focal length
Screen	4k resolution (1000mm×1750mm)

3.2 System Calibration

Based on the system structure shown in Fig. 3, binocular calibration is carried out based on Zhang's calibration method first, and then screen pose calibration is carried out based on the flat mirror with features. As shown in Fig. 4, in the process of binocular calibration, multiple different poses are completed by moving the plane target; in the process of screen pose calibration, multiple different poses are moved by the flat mirror with reflective markers.

3.3 Accuracy Verification and Comparison

Firstly, the measurement of automobile glass by using a CMM is shown in Fig 5. Then, the measurement results of the method proposed in this paper are directly matched with the results of CMM. Most of

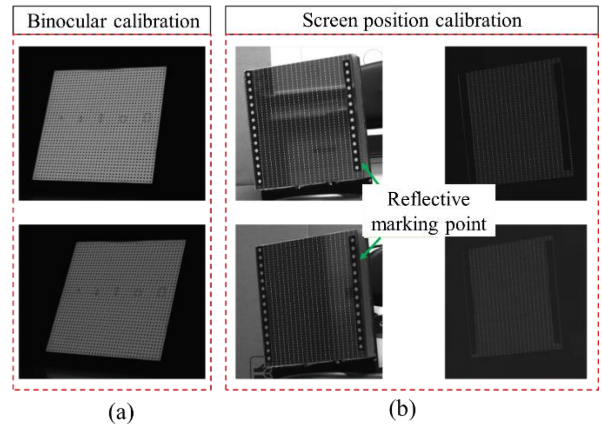

Fig. 4 Schematic diagram of system calibration (a) the images of the camera calibration captured by the camera (b) the images of screen calibration captured by the camera

the regional errors are within 0.01mm, while the boundary errors are relatively large, but still within 0.02mm. This error maybe caused by the truncation of phase information at the boundary. However, this accuracy has been able to meet the vast majority of industrial surface measurement requirements, as shown in Fig 6 (a). The error plots of two-dimensional profiles in the X and Y directions of Fig. 6(b) and Fig. 6(c) are respectively captured. It can be seen that there are some high-frequency components in the measurement errors, which are introduced by phase resolution errors and random noise in the process of CMM.

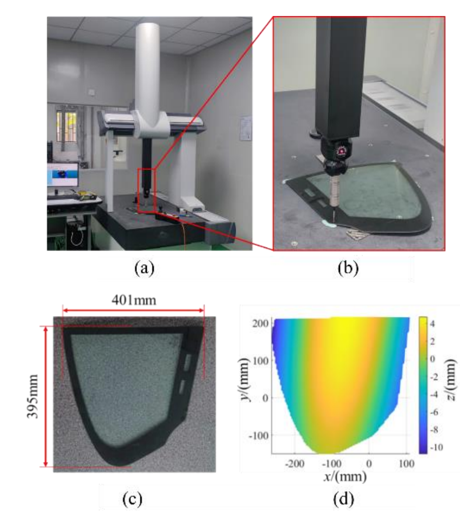

Fig. 5 Measurement of automobile glass by CMM (a) measurement system (b) the measurement details by CMM (c) the measurement of automobile glass and dimensions by CMM (d) the measurement results by CMM

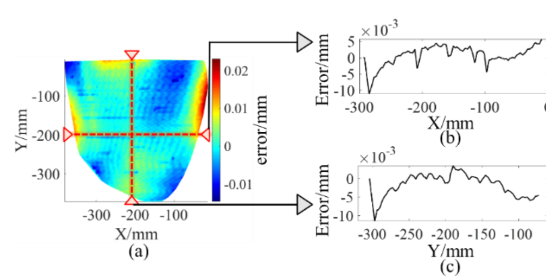

Figure 6 Matching error between our method results and CMM results

(a) the error of CMM matching (b) the matching error of X-direction profile (c) the matching error of Y-direction profile

Further, the phase was solved by the phase shift method based on a sinusoidal continuous fringe diagram, and surface shape was measured based on traditional binocular PMD, and the measurement results were matched with the standard model, the acquired images were shown in Fig. 7 (a). To analyze the measurement accuracy of the traditional PMD, the results of traditional PMD are directly matched with the results of CMM, and the error is analyzed. The results are shown in Fig 7, and it can be seen that the maximum error reaches 0.15 mm, which is nearly an order of magnitude larger than the method proposed in this paper. Through this group of comparative experiments, it is proved that the multi-surface parasitic reflection of glass will have a significant impact on the final measurement accuracy. By contrast, the method proposed in this paper can effectively eliminate parasitic reflection and achieve high-precision measurement of transparent surfaces under the premise of speeding up the measurement speed and simplifying the system structure.

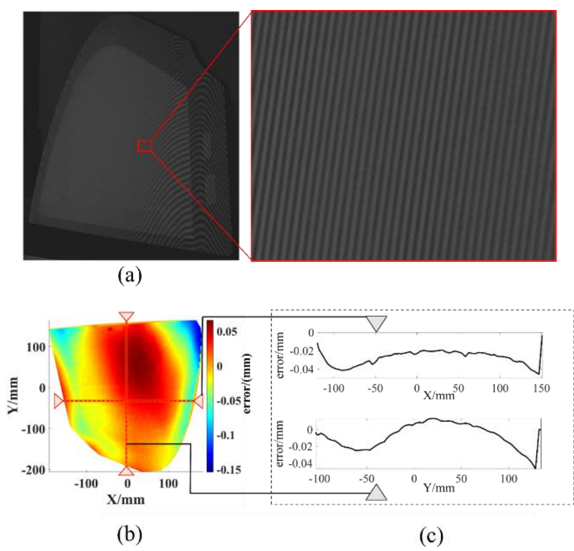

Fig 7. Evaluation of surface shape error of automobile glass based on traditional binocular PMD (a) acquired image (b) the matching error of CMM (c)the error of two-dimensional profile

4. Conclusions

In this paper, a single-frame PMD based on discrete fringe feature images is proposed. The light source containing discrete fringe feature images is laid out and the image reflected by the feature fringe images is captured by the camera to achieve surface shape measurement. Compared with traditional PMD, this method has the advantages of fast speed, dynamic measurement, large surface size measurement, and a transparent surface can be measured. Compared with traditional structured light measurement technology, this method does not need to spray powder on the measured surface to complete the measurement, and can greatly improve the detection speed and accuracy.

At the same time, a screen orientation calibration strategy combining a reflective target and moving flat mirrors calibration method is proposed to improve the calibration robustness. Finally, the measurement system was built and the accuracy was verified by using the front windshield of an automobile. The experiment showed that the measurement accuracy of the system could reach the order of ten microns, which met the measurement accuracy requirements of most industrial reflective transparent surfaces.

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