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A slope-height integrated method for discontinuous specular object measurement using stereo deflectometry

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Abstract
Deflectometry can be used for continuous specular surface measurement with high measurement accuracy due to it is sensitive to slope variation of the measured surface and the surface is reconstructed through slope integration. For the three-dimensional measurement of discontinuous specular objects, the existing phase measurement deflectometry methods use the established relationship between phase information and height value through system calibration. However, the surface form measurement accuracy is low because deflectometry is less sensitive to surface height changes compare to surface slope changes. To overcome this problem, we present a slope-height integrated method in stereo deflectometry. In this approach the measured discontinuous specular object is separated into several continuous regions. Two texture images are captured from two cameras and then the feature points of each sub-region are extracted and matched to obtain the depth data as the height reference of the area. To obtain the gradient field of the measured continuous regions, sinusoidal fringe patterns are projected onto the screen and the deformed patterns reflected via the surface are captured. The phase-shifting method and the optimum three-number fringe selection method are used to calculate the absolute phase. Thus the surface normal of the object under test is acquired. A slope integration algorithm based on gradient field and height reference is implemented in each sub-region respectively, and the three-dimensional shape of the discontinuous specular object is reconstructed. The proposed method combines the advantages of high accuracy slope integral process and the absolute height measurement through texture extraction. This approach leads to high measurement accuracy for the discontinuous specular object. Experimental results show the proposed method is feasible and effective.

Keywords: Optical metrology, Phase measurement deflectometry, Discontinuous specular object, Slope Integration, Feature matching

1. Introduction

With the development of technology, nondestructive measurement has become a common task in many industries. To meet the requirement, various optical methods were explored in recent years[1-2]. Deflectometry has the advantages of non-contact operation, full-field measurement and large dynamic range. These characteristics make it one of the most useful optical methods in the measurement of specular surfaces[3-4].

Since the high reflectivity characteristics of the specular surface, deflectometry system generally utilized a liquid crystal display (LCD) screen to display coded fringe patterns and a camera to capture the deformed patterns reflected by the object under test[5]. Then, the slope field is calculated through the phase information, and the three-dimensional (3D) data of the object can be acquired by slope integration[6]. Deflectometry usually leads to a high measurement accuracy, but it cannot measure the specular object with discontinuous surfaces for the integration algorithm will cause errors at the discontinuous edges[7]. To solve this problem, researchers proposed several methods to calculate the 3D information of each object point independently based on special geometrical system. As the slope integration process is omitted, the discontinuous specular object can be measured[8-9]. However, the measurement accuracy of these methods is usually lower, since deflectometry is less sensitive to surface height change compared to surface slope change. It can be concluded that the current deflectometry methods cannot measure discontinuous specular objects precisely. In order to overcome this limitation, this paper proposed a slope-height integrated method in stereo deflectometry[10]. The discontinuous specualr object is seperated into several continuous sub-regions, and the slope field is searched by stereo deflectometry, then the height information of the feature points of each region is calculated as the height reference, thus the 3D shape of the measured discontinuous object is retrieved.

This article is arranged as follows. Section 2 describes the methodology. The experiment is carried out in section 3 to verify the theory. Finally, the work is concluded in section 4.

2. Methodology

Slope integration is a crucial step in the high-precision measurement of specular objects, but for the discontinuous specular objects, each continuous surface is characterized by a different surface function, which makes it incorrect to directly integrate the slope field of the whole surface. To overcome this challenge, a slope-height integrated method is proposed, the basic idea is to separate the discontinuous specular object into several continuous sub-regions to avoid the integration error . Next, the slope field is calculated and then the accurate 3D information of each sub-region can be acquired by slope integration. Finally, the relative positions between the continuous regions are to be evaluated by feature point extraction method to reconstruct the 3D shape of the discontinuous object.

2.1. Sub-region slope calculation

It is well known that when the light ray illuminates a specular object point, the deflection degree of its corresponding reflected light depends on the slope and height of the point. In other words, if a structured light pattern (such as a sinusoidal fringe pattern) is projected onto the surface of the specular object, the phase change of the deformed pattern reflected by the object is determined by the slope and height of the object surface. Therefore, the geometric relationship between the phase value and slope and height can be established through system parameters. The absolute phase value is able to be obtained by phase-shifting algorithm and phase-unwrapping algorithm, and the slope of the object is the first derivative of the height, so the slope field can be calculated iteratively[11-13]. Then the 3D shape of the measured object can be achieved by slope integration.

To avoid the integration errors mentioned above, the discontinuous object is separated into several continuous sub-regions at first. The continuous specular objects have non-texture characteristics, that is, the gray values of the object points in a continuous region are very similar, so a region growing algorithm is used to segment the discontinuous surface[14]. In each continuous region, an object point is selected randomly as the seed point, then the continuous region can be separated automatically by the gray value difference between the adjacent pixel and the seed point, which provides the feasibility for the implementation of slope integration algorithm.

Then, the stereo deflectometry technology is used to calculate the slope field[15]. In order to explain it clearly, a schematic diagram is shown in Figure 2. When the coded sinusoidal fringe pattern is displayed on the LCD screen, the deformed fringe pattern reflected by the measured object can be collected by camera 1 at an appropriate position. Then, for an object point such as point *M*, a group of incident light l_1 and reflected light i_1 is formed by the point M and its corresponding projection point Q_1 and its imaging point P_1. Since the reflected light i_1 must passes through the optical center simultaneously, the direction of the reflected light is fixed. But the direction of the incident light l_1 have countless possibilities for the position of the object point *M* is unknown, as shown in Figure 1. This is the inherent ambiguity problem of deflectometry technology. To solve this problem, an auxiliary camera 2 is added, and the spatial position of the object point *M* is assumed in a limited space to determine two groups of incident and reflected rays formed by the two imaging points with the object point and their correspondence projection points respectively, which leads to two normal vectors. Once the normal vectors are equal, the assumed position of the object point is considered to be true, and the corresponding slope value is obtained. Based on the above process, the slope field of the measured object surface can be acquired by searching the normal vector of each object point.

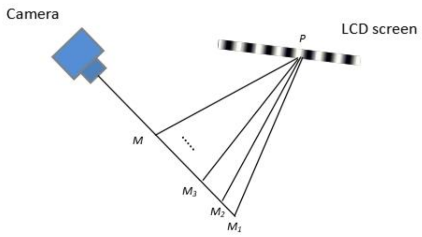


Figure 1. Deflectometry ambiguity problem

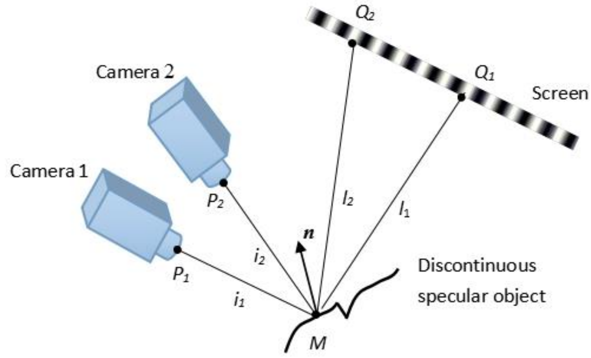


Figure 2. Stereo deflectometry schematic diagram

2.2. Height reference calculation

After calculating the slope field of the object surface, the 3D data of each sub-region can be achieved by slope integration separately. However the absolute position of the sub-regions are still unknown, which caused the confusion of the relative position between different sub-regions.

Because the relative position of the points in a same sub-region has been acquired accurately by slope integration, once the absolute 3D coordinate of a point in that area is obtained, the real position of the whole sub-region can be determined accordingly. The non-texture characteristics of the specular object makes its geometric features mainly concentrated at the edges, thus the proposed method selects the feature points of each sub-region as the height reference point. Two texture images are captured by two cameras respectively, then the harris corner extraction algorithm is used to detect the feature points[16]. When the feature points of the two texture images are matched, the 3D data of the feature points are calculated based on equation 1.

$$\begin{cases}(u_l m^l_{31} - m^l_{11})\ X + (u_l m^l_{32} - m^l_{12})\ Y + (u_l m^l_{33} - m^l_{13})\ Z = m^l_{14} - u_l m^l_{34} \\ (v_l m^l_{31} - m^l_{21})\ X + (v_l m^l_{32} - m^l_{22})\ Y + (v_l m^l_{33} - m^l_{23})\ Z = m^l_{24} - v_l m^l_{34}\end{cases}$$
$$\begin{cases}(u_r m^r_{31} - m^r_{11})\ X + (u_r m^r_{32} - m^r_{12})\ Y + (u_r m^r_{33} - m^r_{13})\ Z = m^r_{14} - u_r m^r_{34} \\ (v_r m^r_{31} - m^r_{21})\ X + (v_r m^r_{32} - m^r_{22})\ Y + (v_r m^r_{33} - m^r_{23})\ Z = m^r_{24} - v_r m^r_{34}\end{cases} \quad (1)$$

where {*X*, *Y*, *Z*} is the absolute position to be solved, m^n_{ij} is the element of camera's projection matrix which can be acquired by camera calibration, (u_l, v_l) and (u_r, v_r) are the feature point's pixel coordinates in two cameras respectively.

Due to the non-texture property of the specular object, feature matching is an important but difficult procedure in this step. Since the feature of the object focuses on its edges, making full use of the geometric shape information of the measured object is a good way to realize feature matching. And a point-line combination method is utilized[17]. First, the edge information of the tested object is extracted; then, the minimum envelope circle formed by the edge points is obtained, and the feature description area of each feature point is acquired by taking the feature point as the center and the radius of the envelope circle as the radius; next, the edge points in the feature description area is counted to form a feature descriptor; finally, the similarity of the feature descriptors is judged by the nearest neighbor rule to identify the corresponding feature point pairs. Subsequently, the absolute position of the feature points can be calculated according to equation 1, which also provide height references for the sub-regions. Then, the 3D shape of the whole discontinuous object is retrieved.

3. Experiment

An artefact of specular step with several discontinuous surfaces as shown in Figure 3 is measured to verify the proposed method. The hardware of the measurement system is composed of a ipad pro as display screen, two LW235M-IO cameras with two 35mm camera lenses, as depicted in Figure 4. The artefact is located in front of the LCD screen. The cameras are focused on the object. The measurement is carried out on an optical platform.

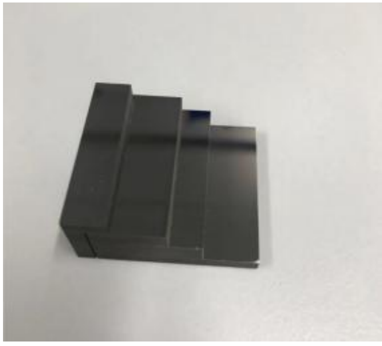


Figure 3. The step artefact

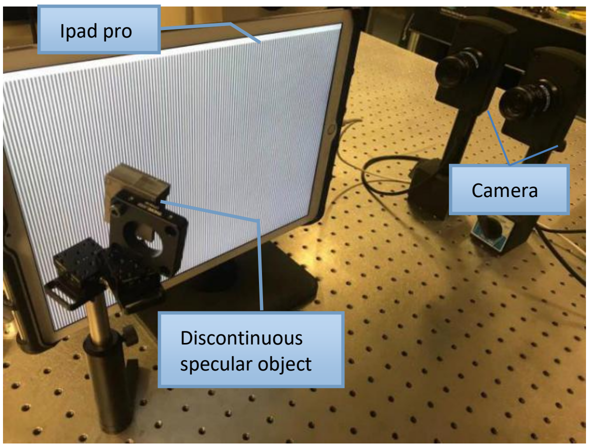


Figure 4. Experimental setup

Two texture pictures were captured by two cameras to segment the discontinuous region and calculate the depth information of feature points of each sub-region. The separated region is shown in Figure 5 and the feature matching result is shown in Figure 6.

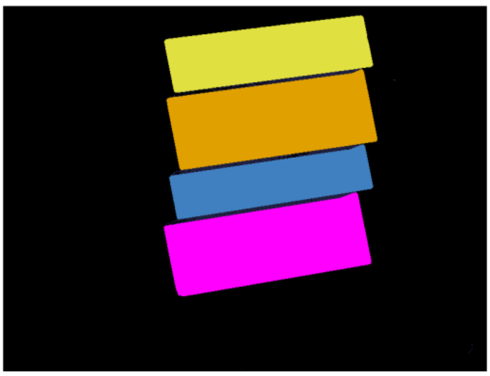


Figure 5. Region segmentation (each color represents a different sub-region)

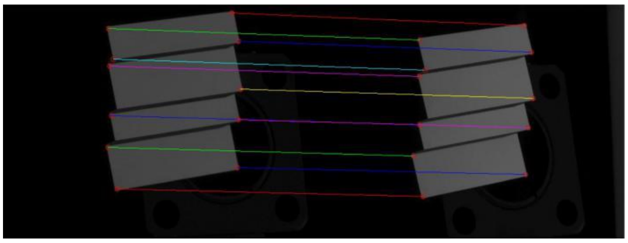
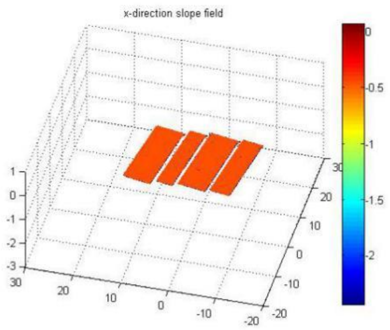
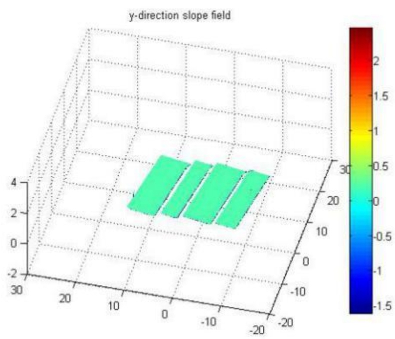


Figure 6. Feature matching result

Then, the coded sinusoidal fringe patterns were displayed onto the LCD screen and the deformed patterns were captured by the two cameras. The phase-shifting method and the optimum three-fringe number selection method were performed to find the corresponding pairs between the camera imaging points and the screen pixels. Thus, the slope field in x-direction and y-direction were acquired, as shown in Figure 7(a) and Figure 7(b) respectively. And the surface form was reconstructed by integration algorithm. Figure 8 shows the reconstructed surface.



(a)



(b)

Figure 7. Slope field. (a) x-direction slope, (b) y-direction slope

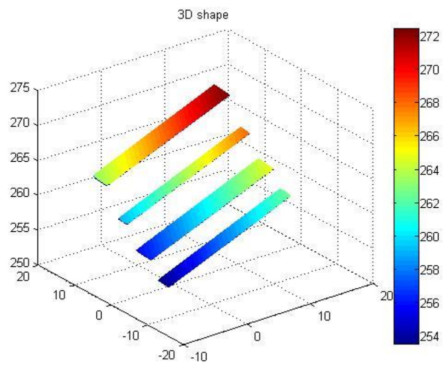


Figure 8. The final 3D shape of the step

To test the performance of the proposed method, the step artefact was also measured by a coordinate measuring machine (within a measuring accuracy of 2 µm). The measurement results from the CMM and the proposed method is shown in table 1. The relative heights of the step measured by the CMM are listed in the second column of the table. The correspondence heights obtained by the proposed method are listed in the third column of the table. And the fourth column of the table are the difference between two measurements. It can be seen that the maximum difference of the artefact specular step is 39.6 µm and the minimum difference is 7.4 µm. From the measurement results, we found that the four discontinuous surfaces of the artefact step are not parallel. Therefore, when using different object points to calculate the relative height between two planes, there will be slight differences in the results, which explains why the error values of the three height distances obtained by the four planes in Table 1 are slightly different. Meanwhile, the 3D data of each continuous region is acquired by slope integration, the error is less than 1 µm, which is far less than other discontinuous specular object measurement methods. Thus, the experimental results demonstrate that the 3D shape of discontinuous specular objects can be measured by the proposed method effectively and accurately.

Table 1 Experimental results of the artificial step (units: mm)

Step Height	Actual distance	Measured distance	Measurement difference
1-2	2.9927	2.9853	0.0074
2-3	3.9282	3.8886	0.0396
3-4	4.9392	4.9279	0.0113

4. Conclusion

This paper develops a slope-height integrated method to measure discontinuous specular objects. Compared with the conventional method, slope integration algorithm is utilized to guarantee the measurement accuracy of the continuous regions. And a region growing method is used to separate the surface into continuous sub-regions to avoid the edge errors caused by integration procedure. Meanwhile, the absolute depth information of the feature points is calculated to acquire the relative position between different sub-regions, then the 3D shape of the tested object can be reconstructed. The experimental results demonstrated that the measuring precision of the discontinuous area can achieve 39.6 µm, and the measurement error of the continuous regions is less than the conventional method. Thus, the proposed method is of significant of discontinuous specular object measurement.

5. Acknowledgements

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