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Study on three-dimensional shape measurement of partially diffuse and specular reflective surfaces with fringe projection technique and fringe reflection technique

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Abstract: Three-dimensional shape metrology using fringe projection technique and fringe reflection technique are effective ways to reconstruct three-dimensional shape for surfaces with different reflectance properties. Fringe projection technique is used for measuring objects with diffuse surfaces and relies on the principle of triangulation, while fringe reflectometry is used for specular reflective specimens based on principle of reflection. While fringe projection directly provides the profile, fringe reflectometry measures the slope of the surface from which the profile is integrated. In this study, the performance of these two fringe based techniques are investigated in relation to sensitivity and accuracy.

Keywords: Three-dimensional shape measurement, fringe projection technique, fringe reflection technique, partially diffuse and specular reflective surface

1. Introduction

Three dimensional (3D) shape measurement techniques have been well researched and increasingly adopted in industry. Applications include but not limited to reverse engineering, quality control, animation, medical diagnosis, and so on. As members of the 3D shape metrology family, Fringe Projection Profilometry (FPP) [1-3] and Fringe Reflectometry Technique (FRT) [4-5] are specifically developed for diffuse and specular targets, respectively.

In some instances, the target to be measured is neither completely diffuse nor fully specular. For these objects both FPP and FRT can be used. Thus it would be necessary to see which approach and under what conditions would be the appropriate choice. This work focuses on comparing the performance of FPP and FRT with both experimental and simulation studies. Samples which can be used for both methods is chosen and tests are conducted with and without fringe processing to see if defects programmed in the sample can be highlighted. To justify this claim, simulations are done.

2. Principles of FPP and FRT

The basic principle of FPP is optical triangulation. A digital projector is used to generate the patterns to be projected, which are then recorded using a digital camera, and processed using the ubiquitous phase shifting routines. As shown in Fig. 1(a), two points in the 3D space can be determined along both incident ray and observing ray in fringe projection profilometric system. Once the system is calibrated, the optical centers O_c and O_p of both camera and projector are uniquely determined. For each camera pixel C , its position in world coordinates can be determined through camera calibration parameters. Moreover, the world coordinates of the related point P from the projector side, which is 'observing' the same target point T , can be determined with both fringe phase and projector calibration parameters. Therefore, the two rays can be determined to measure 3D coordinate of the target point T .

Figure 1. Sketch maps of FPP (a) and stereoscopic FRT (b).

The FRT method is based on the law of reflection and uses a liquid crystal display (LCD) to display the software generated fringe patterns. However, in a common monoscopic FRT system, only the observing ray can be determined as the requirement of two position-known points are satisfied, but the incident ray cannot be determined with only one position-known point S_1 (Fig. 1(b)). Several solutions have been suggested to overcome this issue. The first solution is to regularize this ill-posed problem [4] by assuming the height of the surface is approximately known. This approach is best suited for nearly flat surfaces. The second approach adds one or more additional pattern points along the incident ray by placing the LCD screen at different positions [6]. As shown in Fig. 1(b), the third solution uses a second camera to form a stereoscopic fringe reflectometric system [5]. In this study, the third solution, stereoscopic fringe reflectometry is adopted due to its larger measuring range and no mechanical movement.

3. Experiment

In order to compare the performance of these two techniques in measuring partially diffuse and specular surfaces condition, the measuring system is set up with both FPP and FRT as shown in Fig. 2. The projector used for FPP is 3M™ Pocket Projector MPro120 with a resolution of 768×1,024 pixels. Two USB CCD cameras (Imaging Source® DMK 41AU02 with a resolution of 960×1,280 pixels and DMK 41BU02 also with a resolution of 960×1,280 pixels) are utilized for stereoscopic fringe reflectometric system and shared with fringe projection system. In addition, An LCD screen, PHILIPS® 190S with a resolution of 1,024×1,280 pixels, is used to display fringe patterns for FRT.

Figure 2. Experimental setup.

For FPP, there are a few calibration methods [7-12]. Here, stereovision calibration method [9, 13-14] is adopted with considering the projector as a camera, since its projected phase values can be used to determine the related pixel coordinates in projector. On the other hand, when calibrating fringe reflectometric system, the calibration data will be

obtained both from camera calibration patterns located within the measuring volume, which the tested sample will be placed in, and from the pattern points on screen reflection when the reference mirror is placed at several different tilted positions. Figure 3 shows the calibrated fringe projection profilometric system as well as the fringe reflectometric system after system calibration.

Figure 3. System calibration. (a) Fringe projection profilometric system, and (b) fringe reflectometric system.

A sample with metal texture and several dents on its surface is chosen as the measuring target as shown in Fig. 4(a). The fringe patterns captured with FPP are shown in Fig. 4(b), while those recorded using FRT are shown in Fig. 4(c-d).

Figure 4. Measuring sample and the captured fringe patterns with FPP and FRT. (a) A photo of tested target, (b) a captured fringe pattern with FPP, (c) a captured vertical fringe pattern with FRT, and (d) a captured horizontal fringe pattern with FRT.

By visual observation of the fringe patterns in Fig.4(b-d), the FRT seems more clearly highlight the fringe distortions near the defect. Phase shifting techniques was then adopted for both methods to see if this processing would improve the results for the FPP. With phase shifting plus temporal phase unwrapping technique, the absolute phase can be retrieved as shown in Fig. 5.

Figure 5. Retrieved absolute phase from fringe patterns with phase shifting technique and temporal phase unwrapping. (a) FPP, and (b-c) FRT.

Only the data in region of interest are used in the following processing steps. In FRT, the absolute phase values are used for slope calculation and rough height estimation as shown in Fig. 6(a-b), while the absolute phase can be directly converted to three dimensions in FPP shown in Fig. 6(c). Since the surface is neither completely specular nor fully diffuse both methods show some noise. A least squares integration procedure [15-16] is applied to integrate the slope data with FRT to reconstruct the 3D shape of the tested surface as shown in Fig. 6(d).

Figure 6. Measuring result with FPP and FRT. (a) Slope in y -direction, (b) slope in x -direction, (c) height directly from FPP, (d) height integrated with gradient data from FRT. (e) three-dimensional result from FPP, and (f) three-dimensional result from FRT.

After the in-plane calculation to determine x and y results, the final 3D results are shown in Fig. 6(e-f). Two lines in each height map (Fig. 6(c-d)) are plotted in Fig. 7 to show the difference of the reconstructed height values with these two techniques.

Figure 7. Comparison of one-line profiles in Fig. 6(c-d). (a) Line a , and (b) line b .

The processed result indicates that FPP can also detect the dents but with lower signal-to-noise ratio compared with FRT, which is able to obviously show height variations from the reconstructed 3D shape in Fig. 6(f) even if the gradient data obtained are noisy.

4. Simulation

In order to have a further study on the measurement precision of these two techniques under partially diffuse and specular surface condition, computer simulation is carried out with the same system calibration parameters. The simulated target expressed in Eq. (1) becomes the benchmark for accuracy and precision study.

$$z = 0.003 \times (x^2 + y^2). \quad (1)$$

The in-plane dimensions are within $[-10, 10] \text{ mm} \times [-10, 10] \text{ mm}$ with a sampling resolution of 512×512 pixels.

Firstly, the simulation is set under the preferred condition for each technique. Hence the phase noise with each technique is small. The phase noise standard deviation (STD) is set as 0.0100 radians in FPP, and 0.0100 radians in FRT, which are close to usual values in actual experiment under their preferred condition when 16-steps phase-shifting fringe patterns are used. The reconstructed 3D shapes are shown in Fig. 8(a) with FPP and Fig. 9(a) with FRT. Figure 8(b) and Fig. 9(b) show their related height errors.

Figure 8. Simulation results with FPP under different phase noise conditions. STD = 0.0100 radians: reconstructed surface (a) and height error (b). STD = 0.0390 radians: reconstructed surface (c) and height error (d).

Secondly, the phase noise is set as the same noise level of that in experiment, which can be calculated by using phase after windowed Fourier filtering as phase benchmark [17-18]. In the above experiment, the STD of phase noise in FPP is calculated to be 0.0390 radians, and the STD of phase noise is 0.5667 radians in FRT. The same phase noise is simulated and put into reconstruction for precision study. Figure 8(c) and (d) show the reconstructed 3D shape and height error with FPP, while Fig. 9(c) and (d) show the reconstructed 3D shape and height error with FRT in simulation.

Figure 9. Simulation results with FRT under different phase noise conditions. STD = 0.0100 radians: reconstructed surface (a) and height error (b). STD = 0.5667 radians: reconstructed surface (c) and height error (d).

From the simulation with our configuration, height precisions with FPP are 0.0079 mm when phase noise STD = 0.0100 radians and 0.0307 mm when phase noise STD = 0.0390 radians. With FRT, height precisions are 1.3314×10^{-4} mm when phase noise STD = 0.0100 radians and 1.0991×10^{-4} mm when phase noise STD = 0.5667 radians. It is shown that the precision with FRT is much higher than that with FPP. In addition, under partially diffuse and specular surface condition when phase noise is obviously severer than under their preferred conditions, FRT is not so sensitive to phase noise compared with FPP.

5. Discussion

The accuracy of a fringe-based system does depend on the system calibration. The sensitivity to height with FPP depends on the system geometric configuration as well as the fringe frequency used. With FRT these two factors do not directly determine the sensitivity to height, but the sensitivity to gradient. Thus once a fringe-based system (with FPP or FRT) is fixed, the system sensitivity is already determined. Thus the height measuring precision depends on the phase measuring precision for FPP. But for FRT, the phase measuring precision can only determine the slope measuring precision, and the height measuring precision will be influenced by the integration process from slope data. Hence, the height measuring precision with FRT is determined by the phase measuring precision and the applied integration method. Under the condition of our experiment and simulation, the sensitivity of FRT is higher than FPP.

For measuring partially diffuse and specular surfaces, the main problem for both methods is the phase measuring precision is not good as that under their preferred conditions. But actually there is a property or so-called ascendancy for these partially diffuse and specular surfaces that they can be measured by using both techniques. Thus a natural idea is to combine these two techniques. FPP can be used to estimate the height and used as an input to FRT for slope calculation, so the time-consuming iterative height estimation process can be avoided. Figure 10 shows the result from the combined method.

Figure 10. Reconstructed 3D shape with combined method.

6. Conclusion

Three-dimensional shape metrology using fringe projection profilometry (FPP) and fringe reflectometry technique (FRT) are effective ways to reconstruct three-dimensional shape with different reflectance properties. FPP is used for measuring objects with diffuse surfaces and relies on the principle of triangulation, while FRT is used for specular specimens based

on principle of reflection. While fringe projection technique directly provides the profile, fringe reflectometry measures the slope of the surface from which the profile is integrated. For both methods, projected patterns are computer generated and phase shifting methods are applied.

For fringe projection technique, the sensitivity of three-dimensional measurement directly depends on system geometric configuration. The precision of dimensional measurement directly relies on the system sensitivity and the precision of phase measurement. For the fringe reflection technique, the sensitivity of dimensional measurement does not directly depend on geometry, which actually only directly determines the slope measuring sensitivity. Hence, phase measuring precision only directly yields the precision of slope measurement, which will influence the accuracy and precision of three-dimensional dataset through the following integration process. The performances of these two fringe-based techniques are analyzed with respect to their sensitivity and precision when measuring partially diffuse and specular reflective targets. The measuring precision of both techniques are compared and discussed in simulation and with actual experiment.

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