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Practical Considerations for High-Speed Real-Time 3-D Measurements by the Fringe Projection

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ABSTRACT

Fringe projection is an extensively applied technique for optical three-dimensional (3-D) shape measurements. Although showing favorable performance for motionless objects, it tends to have difficulties to retrieve surfaces globally or locally varying over time. The reason is that common methods developed for static scenes are prone to fail when measuring dynamic processes. Therefore, to facilitate the application of high-speed real-time measurements, we suggest considerations from four aspects to improve conventional fringe projection methods. The first two aspects are related to raising the measuring efficiency, which can be achieved by encoding the measured object robustly yet with less required patterns, and by increasing the rate of pattern projection which is a bottleneck restricting the measuring speed. The third consideration is to obtain accurate 3-D reconstructions by removing unreliable points induced by system and random errors during dynamic measurements. The last one is to handle moving shiny objects as it is supposed to be a time-consuming process for traditional approaches. We believe the mentioned considerations will help ease the efforts to achieve desired results for fast real-time measurements.

Keywords: High-speed real-time 3-D measurements, fringe projection, phase measurement, Fourier transform.

1. INTRODUCTION

The optical three-dimensional (3-D) shape measurement is playing an important role in various fields, including industrial manufacturing, quality control, biological sciences, machine learning, entertainment and so on [1]. Generally, optical measuring techniques can be categorized into two classes, the passive ones and the active ones. For the former, the most well-known strategy is the computer stereo vision by which the depth can be obtained once the corresponding point has been matched from different camera views. An extensive review of the stereo matching algorithms can be found in [2]. As the stereo images are usually captured under ambient illuminations (e.g. fluorescent light, sunlight) free from the governing of users, unknown variations of the ambient light may negatively affect the matching validity of corresponding points in different views [3]. Moreover, this kind of methods tends to be vulnerable to the lack of surface texture [2]. Compared to the passive method, the way of active illumination is able to assign pre-designed code words to the measured surface more robustly, thus reducing the dependence of the surface texture and the impact of changes of the ambient light.

Among active techniques, the fringe projection, benefited from advantages of full field measurement, high resolution and accuracy, is one of the most widely employed methods [4-6]. Traditionally, the fringe projection is proposed to measure static scenes. Therefore, if a scene involving some dynamic processes (e.g. displacements or deformations) needs to be inspected, improvements to the existing methods should to be made for faithful results. This is because new challenges will emerged when a surface is changing over time. In this paper, we are considering four aspects of how to improve the implementation of fast measurements using the fringe projection. To our knowledge, the improvements can be expected from: (1) Efficient inspections with less number of required patterns; (2) Fast measurements by high-speed projection of patterns; (3) Refined 3D results via eliminations of measurement errors; (4) Solution to measure moving shiny surfaces. With these aspects to be taken into account, we believe better performance can be achieved in practical measurements.

2. CONSIDERATIONS TO FACILITATE THE IMPLEMENTATION OF HIGH-SPEED REAL-TIME 3-D MEASUREMENTS

2.1 Efficient Inspections with Less Number of Required Patterns

Traditionally the fringe projection technique is employed for measurements of static scenes, where the measurement time is not a key factor for the recovery of objects as their shapes will not change. For inspections of moving objects, however, positions or contours of objects may vary in an unknown manner with time. Therefore this would inversely affect the 3D reconstructions to some extent, especially for the ones obtained by projecting multiple patterns. Intuitively, there are two ways to increase the temporal resolution (reduce the time cost). The first one is to employ less patterns for the shape recovery and the second to increase the operating rate of measurement system. In this section, we will focus on the former. Theoretically, the idea projecting a single pattern to retrieve surfaces has the highest temporal resolution. A representative technique based on such an idea is the well-known Fourier Transform Profilometry (FTP) [7]. Although being of the superior temporal resolution, the FTP still has several limitations. When a surface with large slope is measured, the problem of frequency overlapping is likely to emerge which can make the filtering of FTP suffer [8]. Besides, the FTP is conventionally applied for measurements of smooth objects because discontinuities or sharp edges may lead to phase ambiguities during the phase unwrapping. To cope with above issues, we developed a two-frame FTP-based real-time fringe technique [9]. To show the real-time performance of the method, we first measured a shaking piece of paper. The measurement result is presented in Fig. 1(a). Then we tested a static box and a human hand which is in front of the box and moving up and down, stretching and clenching. Figure 1(b) shows the measurement result.

Figure 1. Snapshots of real-time measurements of dynamic scenes. (a) Measurement result of a shaking paper; (b) Measurement result of a static box and a moving hand.

Although improvements have been made by the above technique for FTP, due to the nature of spatial filtering, FTP tends to generate unreliable results for very sharp edges or fine structures. Therefore, to circumvent this issue, multi-pattern projection methods are exploited by which the depth is obtained for each pixel independently on the temporal axis. Among the strategies, phase-shifting profilometry (PSP) has merits of high precision, dense measurement and being insensitive to ambient light. As for PSP the efficiency is to some extent subjected to the phase unwrapping strategy, a number of researchers proposed several efficient absolute phase retrieval techniques without projecting extra patterns by embedding additional signal/phase information into the waveforms of the conventional PSP methods [10-12]. Wang *et al.* [12] embedded a period cue and Wissmann *et al.* [11] embedded binary De Bruijn sequence into a four-step phase-shifting sequence. Alternatively, in [13] a novel pattern strategy was proposed for real-time 3-D shape measurement which employs only four patterns to retrieve the absolute phase in the presence of surface discontinuities and isolated objects without ambiguity. With a modified projector where its color wheel has been removed and a high-speed camera, real-time measurements can be achieved at 120 frames per second. Figure 2 shows the result for isolated objects measured in real time.

Figure 2. Real-time measurement results of spatially isolated objects

2.2 Fast Measurements by High-Speed Projection of Patterns

In addition to decreasing the number of patterns, one can also increase the projection rate of patterns to realize high-speed measurements. Currently the common projector can only project a pattern of full gray value (e.g. 8 bits) at a maximum rate of 60-255 Hz, which is a bottleneck to be addressed for measuring fast moving objects. To handle this

issue, researchers reported by [14, 15] built high speed projection devices with which projection rate of 10,000Hz was achieved. While these methods extremely boost the projection rate, it may be not easy to self develop a projection system. Thus with the purpose of increasing the projection speed without modifications of the existing projector, Lei and Zhang [16] presented a technique called squared binary defocusing method (SBM) that is to generate sinusoidal fringe patterns by properly defocusing squared binary structured ones. The usage of the binary pattern drastically improves the projection rate. This is because for common DMD projectors gray image is projected by an integration of illumination with time. For the pattern expressed by binary structure (1 bit) the time of projection can be reduced to the minimum. Subsequently, SPWM, OPWM have been proposed to optimize the implementation of the defocusing fringe projection technique [17].

To further contribute to the defocusing strategy, we presented a bi-frequency tripolar pulse-width-modulation (TPWM) technique [18]. The tripolar means an additional gray level (0.5) is introduced into the original gray levels (0 and 1). The advantage is that an ideal sinusoidal wave can be obtained by a very small amount of defocusing, which preserves a high signal to noise ratio of projected fringes. In the experiment, a rotating fan (300 rotations per minute) was measured which is shown in Fig. 3. The experimental result shows the acquisition speed of the 3-D data can reach 1250 fps.

Figure 3. (a) The measured fan; (b) one captured fringe image of the fan; (c) the reconstructed 3-D result.

2.3 Refined 3D Results via Eliminations of Measurement Errors

For fringe projection techniques, there are four main causes of errors [19]: (1) the actual phase shift is not rigorously equal to the expected one, which is usually treated as mis-calibration; (2) the projection of imperfect sinusoidal pattern because of the presence of harmonics or gamma distortion from the projector ; (3) random noise from the camera sensor; (4) motions that violate the assumption of the phase retrieve by which a certain pixel is supposed to correspond to a fixed measuring point in the sequence of captured phase-shifting images.

For the case of (1), we suggest to use DLP or LCD projectors since the phase shift is realized digitally. For the second cause of errors, one can handle it by either pre-distorted the pattern [13] or compensating the phase error [20]. To cope with the error in (3), it is recommended to exploit fringes of relative high frequency, which can also alleviate the adverse influence of the random errors without usage of extra images. For the case of (4), to handle these outliers caused by motions, we introduce a four-stage framework that allows fully automatic identifications and removals of the unreliable points [21]. With the assists of the phase map, modulation maps, phase distributions and filtering, the outliers can be detected accurately. The measurement result is shown in Fig. 4. It can be seen that the outliers are gradually eliminated with the proceeding of the framework and finally none of obvious invalid points can be observed.

Figure 4. 3-D reconstruction result of a moving hand: (a) 3-D result without invalid pixels identification; (b) 3-D result after the first step; (c) 3-D result after the second step; (d) 3-D result after the third step; (e) accurate 3-D result after all the steps.

2.4 Solution to Measure Moving Shiny Surfaces

For fringe projection techniques the major problem faced when they are used to inspect reflective areas is that the 3-D depth sensing is entirely relied on the fringe analysis of captured patterns. Once the image pixel is saturated as a result of the intense reflected light at a highly reflective point, no fringe can be recorded and used for the 3-D shape reconstruction. Thus to cope with shiny objects, Zhang *et al.* [22] proposed a high dynamic range measuring technique based on the multi-exposure strategy. With the same principle, Waddington and Kofman *et al.* [23] developed a technique which adjusts the illumination intensity of the projector to avoid the camera saturation. For the above methods, however, they were developed for still objects and thus may not be appropriate for measuring dynamic scenes.

Therefore, to develop a method for fast measurements of varying reflective surfaces, we present a novel fringe projection strategy. In the work, to lower the sensitivity to motions we only employ four patterns among which three images are phase-shifting fringes and the remaining one is an image of digital speckles. The three-step phase-shifting algorithm is applied for the phase measurement. Because of the camera saturation caused by highlights, the obtained phase for the shiny region is prone to be erroneous. Therefore, to correct phase errors we utilize another camera viewing from a different angle to build a stereo fringe projection system. To find the corresponding area in these cameras, we use the speckle image to mark the local region uniquely. Experimental result of a rotating is shown in Fig. 5. To show the improvement, in the video we also compared our result with the one without any error compensation, which is shown by the last two windows in the first row. From the results by the method shown in the last two windows in the second row, the reflective thumb drive was correctly measured while it was rotating.

Figure 5. A screenshot of the measurement video.

3. CONCLUSION

In the paper, we summarize four aspects worthy of being considered to facilitate high-speed real-time 3-D measurements with fringe projection. The first aspect is to efficiently and robustly encode the projected light while using less patterns. The second one is to increase the rate of pattern projection as this rate is usually the bottleneck limiting the measuring speed. In the third consideration, we briefly analyze major error causes that may emerge for fringe projection methods and review some effective methods to remove the errors. Last but not least, we introduce a technique to measure moving glossy surfaces which poses a challenge for traditional fringe projection techniques for high dynamic range inspections. With the above considerations, better performance can be obtained for practical high-speed real-time measurements.

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