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Experimental study for the influence of surface characteristics on the fringe patterns

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Abstract

Fringe projection profilometry (FPP) has been widely used for three dimensional (3D) imaging and measurement. The fringe acquisition of FPP mainly depends on the diffuse light from the surface of objects, thus the characteristics of object surface have significant influence on phase calculation. One of the essential factors related to phase precision is modulation index, which has a direct relationship with the surface reflectivity. This paper presents a comparative study which focuses on the modulation index of different materials. The distribution of modulation index for different samples is statistical analyzed, which leads to the conclusion that the modulation index is determined by the diffuse reflectivity rather than the type of materials. This work is helpful to the development of effective de-noising algorithms to improve the measurement accuracy.

Keywords

fringe analysis, modulation index, reflectivity, FPP, 3D shape measurement

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Experimental study for the influence of surface characteristics on the fringe patterns

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ABSTRACT

Fringe projection profilometry (FPP) has been widely used for three dimensional (3D) imaging and measurement. The fringe acquisition of FPP mainly depends on the diffuse light from the surface of objects, thus the characteristics of object surface have significant influence on phase calculation. One of the essential factors related to phase precision is modulation index, which has a direct relationship with the surface reflectivity. This paper presents a comparative study which focuses on the modulation index of different materials. The distribution of modulation index for different samples is statistical analyzed, which leads to the conclusion that the modulation index is determined by the diffuse reflectivity rather than the type of materials. This work is helpful to the development of effective de-noising algorithms to improve the measurement accuracy.

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1. INTRODUCTION

Fringe projection profilometry (FPP) is one of the most popular non-contact methods for three dimensional (3D) imaging and measurement[1]. Recently, its application has extended to a broad range including industry, cultural heritage, medicine, etc[2]. With FPP, ideal sinusoidal patterns are projected onto the object surface which results in deformed fringe patterns. The images of the deformed fringe patterns are captured by a camera and then processed to reconstruct the profile of objects. However, the broad application means that the characteristics of object surface are complex. The surface may dark or light, rough or shiny, which makes the fringe patterns captured by camera surfer from abnormal intensity. So it is difficult to reconstruct the object accurately.

Some fringe capture and processing methods have been proposed to eliminate the negative impact of the specific surface. Zhang et al.[3] introduced a polarizing filter for capturing the fringe patterns from high-reflective sculptured surfaces. Kowuschika et al.[4] changed the direction of projected light to compensate for the influence of specular reflections or shadows. Zhang et al.[5] introduced a high dynamic range (HDR) scanning technique by taking different exposure times, which successfully measured objects with obvious variation of surface reflectivity. Jiang et al.[6] also used multiple exposure times to generate HDR fringe images, while different fringe image fusion algorithm is introduced to generate high signal-to-noise ratio (SNR). Feng et al.[7] divided the measured surface into several groups based on its histogram distribution of reflectivity, then adaptively predicted the optimal exposure time for each group.

Although many methods have been developed to deal with the influence of specific surface characteristics, there has not any comparative study for different materials. This paper intends to research the influence of surface characteristics on the fringe patterns by selecting some typical materials and making comparative analysis. Section 2 introduces the principle of FPP and fringe analysis. Section 3 focus on the experiments, including sample selection, experiment results and analysis. Section 4 summarizes the paper.

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2. PRINCIPLE

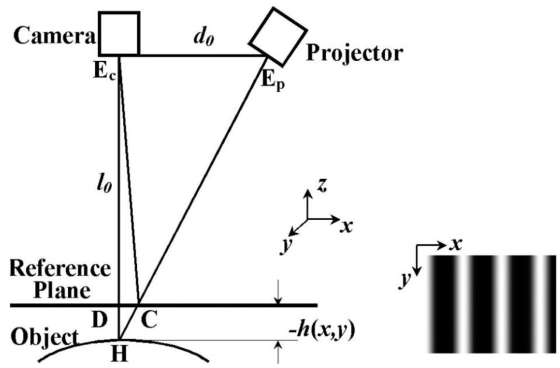

Fig.1 FPP classic system

2.1 Principle of FPP

A typical fringe projection profilometry (FPP) system is shown in Fig.1, which consists of a fixed camera and projector[8]. The projector illuminates the surface of object with specific fringe patterns, while the camera captures the deformed fringe patterns modulated with the height of the object. And then the phase information, which has a potential relationship to the height of the object, can be calculated with captured deformed fringe patterns. To obtain the relationship between phase and height, the reference plane is introduced by employing a plane target perpendicular to the principal axis of the camera. We assume that the distance between the camera and the reference plane is large enough so that the reflected light captured by CCD is not only parallel to each other but also vertical to the reference plane. In this case, the height of the object h can be expressed with the phase information φ and system parameters as follows

$$h = \frac{l_0 \varphi(x)}{\varphi(x) - 2\pi f_0 d_0} \tag{1}$$

where l_0 is the distance between the camera and object, d_0 is the distance between camera and project.

2.2 Phase-shifting algorithm

Phase-shifting algorithm is widely used to calculate the phase φ in FPP due to its high precision and robustness. The phase-shifted fringe pattern of the i^{th} step captured by the camera can be formulated as follows

$$I_i = A_{(x,y)} + B_{(x,y)} \cos\left(\varphi_{(x,y)} + \frac{2\pi i}{N}\right), \quad i = 1, \cdots, N \tag{2}$$

where N denotes the total step number of phase-shifting. Then the phase φ can be calculated with the following expression

$$\varphi_{(x,y)} = \arctan\left[\sum_{i=1}^{N} I_i \sin\left(\frac{2\pi i}{N}\right) \Big/ \sum_{i=1}^{N} I_i \cos\left(\frac{2\pi i}{N}\right)\right] \tag{3}$$

Meanwhile, the average intensity A and modulation intensity B can also be determined as follows[9]

$$A_{(x,y)} = \frac{1}{N}\sum_{i=1}^{N} I_i \tag{4}$$

$$B_{(x,y)} = \frac{2}{N}\sqrt{\left[\sum_{i=1}^{N} I_i \sin\left(\frac{2\pi i}{N}\right)\right]^2 + \left[\sum_{i=1}^{N} I_i \cos\left(\frac{2\pi i}{N}\right)\right]^2} \tag{5}$$

2.3 The modulation index

The fringe modulation index γ can be expressed with the average intensity A and modulation intensity B as $\gamma=B/A$. Because the signal-to-noise ratio (SNR) has a positive correlation with the modulation index, to acquire phase φ with high precision, FPP tends to make the captured fringe patterns have modulation index as high as possible. To demonstrate the factors influencing the modulation index, it's helpful to investigate the expression of γ from another viewpoint[6]. The illumination of projector can be written as ideal distribution

$$I_i^p = a + b\cos\left(\varphi + \frac{2\pi i}{N}\right), \quad i = 1,\cdots,N \tag{6}$$

where constant a and b can be set in the computer to adjust the intensity of the fringe patterns. Then the fringe patterns capture by the camera can be express as

$$I_i = s\left(r_{(x,y)} I_i^p + I_{(x,y)}^a\right), \quad i = 1,\cdots,N \tag{7}$$

where s denotes the camera's sensitivity to light, $r_{(x,y)}$ the surface reflectivity and $I_{(x,y)}^a$ the ambient light. Comparing with Eq. (1), we have

$$A = s\left(r_{(x,y)} a + I_{(x,y)}^a\right), \quad B = s r_{(x,y)} b \tag{8}$$

Thus the modulation index can be written as

$$\gamma_{(x,y)} = \frac{B}{A} = \frac{r_{(x,y)} b}{r_{(x,y)} a + I_{(x,y)}^a} \tag{9}$$

It can be noticed that the surface reflectivity $r_{(x,y)}$ effects the modulation index significantly. Therefore, the influence of object surface characteristics (mainly related to $r_{(x,y)}$) on the fringe patterns can be evaluated with the modulation index.

3. EXPERIMENTS

To evaluate the influence of different materials on the fringe patterns, we select some typical samples. A commercial projector Hitachi CP-X260, 1024×768 pixels, is used to structural illumination. Five steps phase-shifted fringe patterns are generated and then projected onto the surfaces of samples, and then the deformed fringe patterns are captured with the camera DUNCANTECH MS3100, 1280×959 pixels. And then the modulation index could be calculated. As the modulation index corresponding to different samples have values on the same scale ($\gamma \in [0,1]$), analysis and comparison for the modulation index should be convenient and convincing.

3.1 Sample selection

The choice of materials should be mainly take into account the universality and typicality for FPP. Moreover, in order to make sure the study is useful to real purpose, all the materials involved in the experiment should be widely used in industry or life. We select 5 types of materials and corresponding samples which are all widely used in industry, medical application and daily life, etc. In order to ignore the inter-reflection of the surface, only the samples with simple shape are selected.

The materials and samples we chose are listed below:

(1)Plastics. In the experiment we choose a plastic card as the sample.

(2) Metal. In the experiment we choose a piece of Aluminum alloy as the sample.

(3) Ceramic. In the experiment we choose a ceramic cup as the sample.

(4) Leather. In the experiment we choose a notebook with leather cover as the sample.

(5) Paper. In the experiment we choose a piece of white paper as the sample.

3.2 Experiment & results

We do the experiment in same light condition to make sure the fluctuation of the ambient light can be ignored. For each sample, one of the captured fringe image, the distribution of γ in selected area and its histogram are demonstrated.

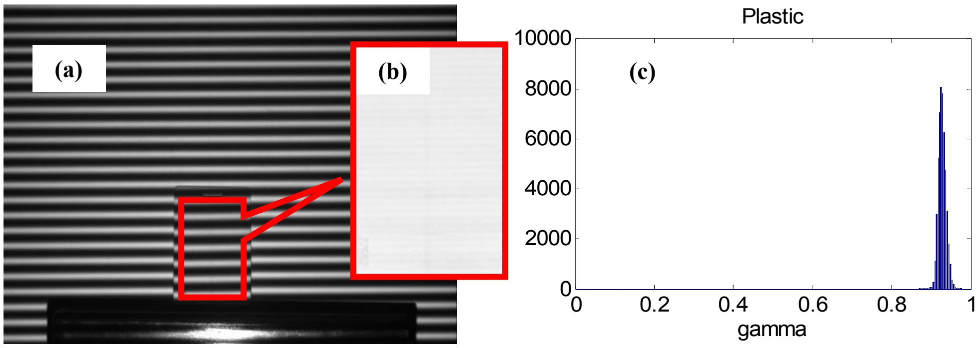

Fig 2. Experiment results for plastic (an access card): (a) the captured fringe image and selected area (marked with red box); (b) the distribution of γ in selected area; (c) the histogram of (b).

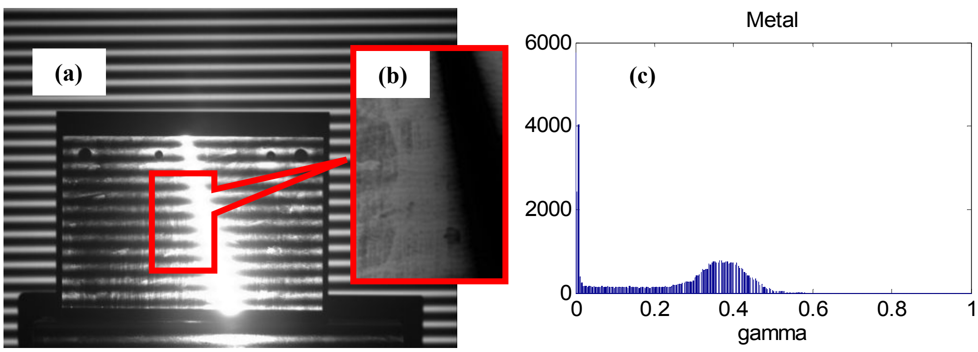

Fig 3. Experiment results for metal (Aluminum alloy): (a) the captured fringe image and selected area (marked with red box); (b) the distribution of γ in selected area; (c) the histogram of (b).

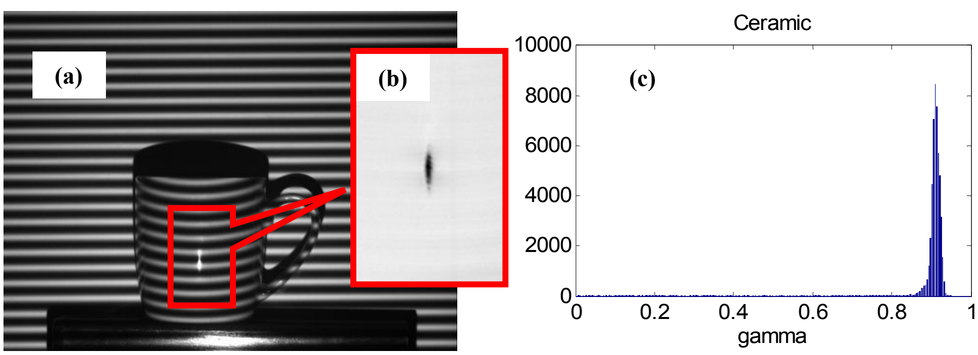

Fig 4. Experiment results for ceramic (a cup): (a) the captured fringe image and selected area (marked with red box); (b) the distribution of γ in selected area; (c) the histogram of (b).

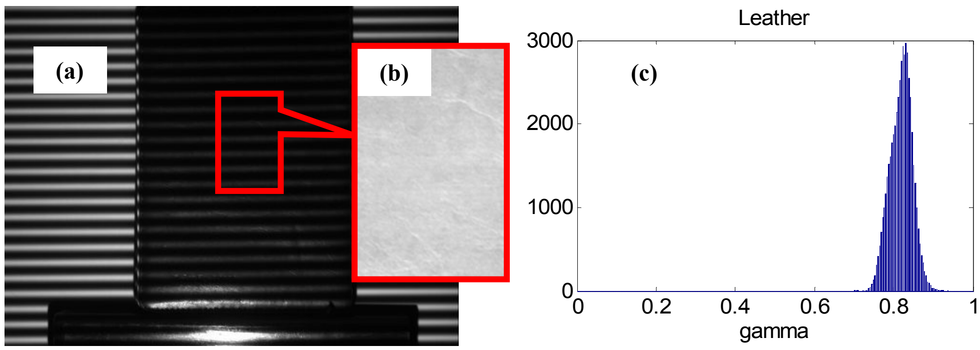

Fig 5. Experiment results for leather (a notebook): (a) the captured fringe image and selected area (marked with red box); (b) the distribution of γ in selected area; (c) the histogram of (b).

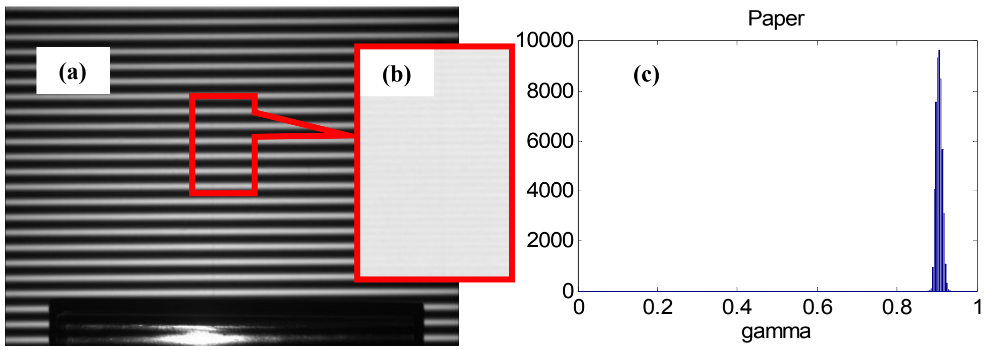

Fig 6. Experiment results for paper: (a) the captured fringe image and selected area (marked with red box); (b) the distribution of γ in selected area; (c) the histogram of (b).

3.3 Analysis

As mentioned above, to acquire phase φ with high precision, FPP tends to make the captured fringe patterns have modulation index as high as possible. From the experiment results, it can be clearly seen that most samples have distinct modulation index γ, whilst the plastic card and the paper have similar γ distribution. The plastic card, the leather cover and the paper have high γ values thought the selected areas, while the cup presents low γ values in shiny area. The piece of Aluminum alloy has relative low γ values especially in the shiny area.

It can be seen that different materials may present similar γ distribution, i.e., the plastics and the paper may both have high γ values, while the metal and the ceramic both have low γ values in the shiny area. We infer that the type of materials is not the determinative factor. The difference of γ distribution is more depended on the diffuse reflectivity (shiny or not) of the surface.

4. CONCLUSION

This paper presents a comparative study which focuses on the characteristics of object with different material. In order to get comprehensive data, we do the experiment for different material in FPP system. The influence properties obtained could be employed for the development of effective de-noising algorithms to improve the measurement accuracy. The future work will be focused on the influence of other characteristics such as color, shape, ambient etc. and then creating an algorithm to compensate the distortion for different material surface condition.

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