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# High dynamic range imaging for fringe projection profilometry with single-shot raw data of the color camera

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ABSTRACT

It is a challenging issue to get satisfied results in terms of 3D imaging for shiny surface with fringe projection profilometry (FPP), as the wide variation of surface reflectance for shiny surface will lead to bad exposure, which requires the high dynamic range imaging (HDRI) technique. HDRI with monochromatic illumination and single-shot raw data of the color camera is presented in this paper. From the single-shot raw data, 4 monochrome sub-images corresponding to R, G, G and B channels can be separated respectively. After the attenuation ratios between R&G, G&B channels are calibrated, an image with higher dynamic range can be synthesized with the 4 sub-images, which can help to avoid the impact of bad exposure and improve the accuracy of phase calculation. Experiments demonstrate the validity of proposed method for shiny surface.



## 1. Introduction

Optical three-dimensional (3D) imaging, which is an important technique that can record and analysis the real world, has developed a lot under the push of growing demands and advances in technology. It has been widely employed in various fields, including industrial manufacturing, culture heritage, medical diagnosis, entertainment [1]. As a method with the advantages of high accuracy, high data density and flexible setup, fringe projection profilometry (FPP) has attracted a lot of attention for a long period [2]. From the work principle of FPP, it can be seen that rough surface with approximate Lambert's reflectance is the most suitable target for 3D imaging with FPP. However, with the expanding application of FPP, the observation targets become more and more complex, which introduces quite different surface reflectance. Depending on the different light reflectance, the surfaces of opaque objects can be generally divided into three categories: the rough surface, the shiny surface and the specular surface [3]. As shown in Fig. 1, shiny surface has the reflection characteristics between rough surface and specular surface, which presents hybrid reflectance containing partial diffuse reflection and partial specular reflection. It is well known that for certain incident light intensity, diffuse reflection will lead to global low reflect light intensity while specular reflection will lead to high reflect light intensity in specific direction. In this case, imaging for shiny surface will surfer form bad exposure, including under exposure (corresponding to diffuse reflection area) and over exposure (corresponding to specular reflection area), which has negative impact on the accuracy of information acquisition. Therefore, 3D imaging for shiny surface with traditional FPP is hard to get highly accurate 3D reconstruction results. However, as most objects made of metal or ceramic naturally have shiny surface and take a large proportion in common industrial and civilian products, the disadvantages of traditional FPP for shiny surface greatly limit its application in the fields of industrial inspection and culture heritage.

The main attempt to realize 3D imaging for shiny surface with FPP focuses on achieving high dynamic range imaging (HDRI) by modifying the illumination and acquisition. Kowarschik et al. [4] change the intensity of structural illumination to eliminate the bad exposure. Meanwhile, to compensate the influence of specular reflections or shadowed areas, up to 15 light projection directions are used. In order to avoid over and under exposure in the image, Koninckx et al. [5] adjust the local intensity ranges in the projected patterns based on a crude estimate of the scene geometry and reflectance characteristics. Ri et al. [6] define the phase reliability evaluation value using the Fourier transform (PREV/FT), which is

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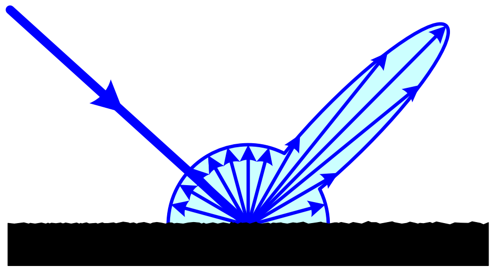

**Fig. 1.** The reflectance of shiny surface.

applied to merge data with different exposure times and acquisition directions. Zhang et al. [7] analysis the characteristics of fringe images used in phase-shifting and then produce the final fringe images from multi-exposure images pixel-by-pixel by choosing the brightest but unsaturated corresponding pixels from one exposure. Liu et al. [8] first set minimal and maximal high precision measurable gray scale by experiment, then calculate the mask image sequence, and finally generate each pixel of the fringe images by selecting the brightest within the set range corresponding pixel from one set of fringe images. Jiang et al. [9] fuse the raw fringe patterns acquired with different camera exposure time and illumination intensity to generate a synthetic fringe image. Fringe image fusion is achieved by choosing the pixels in the raw fringes with the highest fringe modulation intensity. In summary, some approaches change the projection direction with the help of additional mechanical device or projector, which will increase the complexity of system. Some approaches reduce the maximal intensity of projector to avoid over exposure, which will lead to lower fringe quality. All of these approaches rely on multiple exposures with different system configuration, which take the expense of low time efficient. Therefore, it is worth to present a method that can generate high dynamic range image within relatively short time, which is the motivation of this work.

HDRI with single-shot raw data of the color camera is presented in this paper. A fringe pattern is projected based on monochromatic illumination and the deformed fringe image is captured in single-shot fashion using a color camera. From the single-shot raw data, 4 monochrome sub-images corresponding to R, G, G and B channels can be separated respectively. The sub-images have different intensity attenuation because the quantum efficiency of R, G and B channels are quite different for specific wavelength. After the attenuation ratios between R&G, G&B channels are calibrated, a higher dynamic range (HDR) image can be synthesized with the 4 sub-images. The following content is organized as follows: Section 2 briefly reviews the principle of FPP and then explain the necessity of HDRI. Section 3 presents the details of proposed HDRI with single-shot raw data. Section 4 shows a group of experimental results which demonstrate the validity of proposed approach. Section 5 is the conclusion.

## 2. FPP for shiny surface

### 2.1. Principle of FPP

The typical work process of FPP is schematically shown in Fig. 2. Standard fringe patterns are generated and projected onto the surface of object, and the deformed fringe images modulated by the 3D shape of the surface are captured by the camera. Then the wrapped phase map $\boldsymbol{\varphi}_{\mathrm{w}}$ modulo $2\pi$ can be calculated and unwrapped into continuous phase map $\boldsymbol{\varphi}_{\mathrm{u}}$, with which the 3D range image $\mathbf{X}$ can be reconstructed. Generally, there is a certain mapping form $\boldsymbol{\varphi}_{\mathrm{u}}$ to $\mathbf{X}$, which is expressed as $\mathbf{X} = h_{\boldsymbol{\theta}}(\boldsymbol{\varphi}_u)$. The system parameters $\boldsymbol{\theta}$ are determined by system model and configuration, which can be estimated with system calibration. Once the system is calibrated, the result of 3D reconstruction only depends on the phase information $\boldsymbol{\varphi}_{\mathrm{u}}$. Thus phase recovery is the key step of FPP. One of the most commonly used methods to calculate the wrapped phase is the well-known phase-shifting algorithm, which can be formulated as follows:

$$\varphi_w = \arctan\left[\sum_{k=1}^{N} I_k^c \sin\left(\frac{2\pi k}{N}\right) \Big/ \sum_{k=1}^{N} I_k^c \cos\left(\frac{2\pi k}{N}\right)\right] \tag{1}$$

where $N$ is the total step number of phase-shifting, and $I_k^c$ is the $k$th phase-shifted fringe image. If there is any abnormal factor when $I_k^c$ captured, extra error will be introduced into the phase information, and then reduces the accuracy of final 3D reconstruction.

### 2.2. Captured fringe image from shiny surface

In general, the captured fringe image $I_k^c$ can be written as:

$$I_k^c = s\left(rI_k^p + I_a\right), \quad k = 1, 2, \ldots, N \tag{2}$$

where $s$ is the camera sensitivity, $r$ is the surface reflectance, $I_k^p$ is the standard fringe pattern projected to the surface, and $I_a$ is the ambient light. For a certain camera, $s$ is a constant. When the system is working in the dark, the ambient light can be ignored, which means $I_a \approx 0$. The standard fringe pattern is generated in computer, so $I_k^p$ can be determined in advance. Practically, the only uncontrollable factor is the surface reflectance $r$, especially for shiny surface. As shown in Fig. 1, the reflectance of shiny surface is relatively small in general case, while in some directions, it will become very large. Thus the intensity of captured fringe image reflected from shiny surface may vary in a large range. Acquisition of such fringe image with traditional methods will lead to bad exposure and then introduce error to the calculated phase map. Therefore, HDRI should be employed to avoid the bad exposure and improve the accuracy of phase calculation.

## 3. HDRI with color camera

Traditional HDRI for FPP of shiny surface mainly relies on multiple exposures with different system configuration. Options of either the illumination or the acquisition or both of them are modified during multiple exposures to achieve different responses to the intensity of fringe image. Final HDR image is generated from selection or combination of the multiple images. However, due to multiple exposures, all of these approaches take the expense of low time efficient. To overcome this disadvantage, HDRI with single-shot raw data of the color camera is proposed.

### 3.1. Principle

For single-chip color camera, Bayer filter mosaic shown in Fig. 3(a) is commonly used to separate pixels into R, G and B channels. Due to the wavelength selectivity of Bayer filter, the three channels have different quantum efficiency curves versus wavelength. Therefore, with monochromatic illumination, e.g. blue light, the quantum efficiency of R, G and B channel will has the relationship of $e_b > e_g > e_r$. In this case, the Bayer filter can be regarded as a pixel varying neutral density filter [10], the brightness of which demonstrates its intensity attenuation, as shown in Fig. 3(b). For high attenuation such as $e_r$, it can accept very high luminance without saturation. While for low attenuation such as $e_b$, it is more sensitive to low luminance, as shown in Fig. 3(c). When the fringe pattern is projected with monochromatic illumination and the

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