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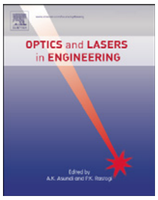

# High dynamic range fringe acquisition: A novel 3-D scanning technique for high-reflective surfaces

Hongzhi Jiang*, Huijie Zhao, Xudong Li

*Beihang University, School of Instrumentation Science and Opto-electronics Engineering, XueYuan Road no. 37, HaiDian District, Beijing 100191, China*

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This paper presents a novel 3-D scanning technique for high-reflective surfaces based on phase-shifting fringe projection method. High dynamic range fringe acquisition (HDRFA) technique is developed to process the fringe images reflected from the shiny surfaces, and generates a synthetic fringe image by fusing the raw fringe patterns, acquired with different camera exposure time and the illumination fringe intensity from the projector. Fringe image fusion algorithm is introduced to avoid saturation and under-illumination phenomenon by choosing the pixels in the raw fringes with the highest fringe modulation intensity. A method of auto-selection of HDRFA parameters is developed and largely increases the measurement automation. The synthetic fringes have higher signal-to-noise ratio (SNR) under ambient light by optimizing HDRFA parameters. Experimental results show that the proposed technique can successfully measure objects with high-reflective surfaces and is insensitive to ambient light.

## 1. Introduction

With the development of the manufacturing industry, a lot of objects with high-reflective surfaces such as aluminum alloy or titanium alloy turbine blades need to be profiled quickly and accurately. Measuring the 3D shape of shiny surfaces has always been a big challenge for optical metrology. Among the various optical metrology techniques, contact coordinate measuring machine (CMM) is a typical 3-D shape measurement system for high-reflective surfaces, as it is not sensitive to the optical properties of part surface. However, the low CMM measurement speed is a major problem for its application on shiny surface measurement. On the contrary, image-based optical non-contact 3-D shape measurement techniques [1] can measure very fast, but the measurement precision is associated with optical properties of part surface. Good results are obtained usually for Lambertian surface [2] from which the light reflected diffuses hemispherically in all directions. When measuring the shiny surfaces with a large reflectivity variation range, these optical methods including laser range scanning, stereo vision, cannot work properly. It should be emphasized that we are not interested in specular surface where Lambertian law does not hold, and the illumination fringes are specularly-reflected like reflecting from a mirror. Some optical 3-D shape measurement techniques [3–6] have been proposed to treat such specific specular surfaces. In real case, many high-reflective surfaces such as the aluminum alloy with visible machining marks are still treated as Lambertian one, although glint may happen in some regions. To date, no good method and no commercial product can effectively handle the shiny surfaces. The methods introduced in Ref. [7,8] use polarizing filters, which require surfaces to reflect enough diffused light because polarizing filters drastically reduce the output light intensity of a projector and the incoming light of a camera. Consequently, this makes measuring of surfaces that reflect a small amount of diffused light more difficult. The method proposed by Kowuschika et al. [9] changes the direction of projected light to compensate for the influence of specular reflections or shadows. This is a time-consuming procedure. Baba et al. [10,11] proposed a laser rangefinder and constructed a 360° shape measurement system for Lambertian objects and specular objects. Zhang [12] introduced a high dynamic range scanning technique by taking different exposures. However, two problems remain unsolved so far. Firstly, the exposures of a camera in Zhang's method, although changeable by adjusting the aperture of the camera lens, are not quantified. Secondly, measurement can be only executed where there is no ambient light because ambient light leads to low signal-to-noise ratio (SNR) of the fringe images.

For practical use of the optical 3-D measurement system in the field, the ambient light during measurement would affect the validity of the measurement. Waddington [13] presented analyses of fringe-projection measurement-precision sensitivity to object illuminance and fringe-pattern gray level. This method only

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* Corresponding author. Tel.: +86 10 82317191 802; fax: +86 10 82315884.
*E-mail address:* jhz1862@hotmail.com (H. Jiang).

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adjusted maximum fringe-pattern gray level to tolerate ambient light and avoid image saturation, which leads to decrease the SNR of the fringe images when the illuminance from ambient light is higher.

A new 3-D scanning technique for high-reflective surfaces based on phase-shifting and stereovision techniques [14] is presented in this paper. In order to solve the problem caused by high-reflective surface, high dynamic range fringe acquisition (HDRFA) is proposed. Here, HDRFA denotes imaging from high-reflective surfaces covered by projected fringes, which generates a new fringe image free from saturation and darkening by fusing several different raw fringe images. The highest fringe modulation intensity other than the brightest fringe intensity [12] is applied to fringe image fusion algorithm, which produces the pixels of the new fringe images. This change maximizes the usage of highest modulation intensity, and therefore increases the SNR as well as measurement dynamic range under ambient light. The HDRFA was implemented and tested in our previously developed 3-D scanning system [15], which included two digital cameras, one projector, and one computer. Our experiments demonstrated that the proposed technique can successfully measure high-reflective surfaces, which are insensitive to ambient light.

The paper is organized as follows. Principles of the proposed method are explained in Section 2. Test system and experimental results are discussed in Section 3 and conclusions are presented in Section 4.

## 2. Principle

Phase-shifting method [16] is widely used in 3-D shape measurements due to its fast measurement speed comparing to CMM measurement, less sensitivity to surface reflectivity variations and high spatial resolution [17]. However, when measuring shiny surface, phase shifting method like other optical techniques cannot retrieve fringe phase correctly for the saturation region in the acquired fringe images. Also, the measurement quality is also poor for the dark region where the SNR of fringes is low.

HDRFA fuses a new fringe image from different raw fringe images, acquired by controlling the exposure time of a camera and also by adjusting the light intensity of projected fringes. This approach not only avoids the saturation problem, but also dramatically enhances fringe contrast and improves the SNR of fringe images in dark areas. Through HDRFA, the dynamic range of a fused fringe image can be extended by fusing several differently exposed images. Some measures are introduced to minimize the ambient light effect on fringes and to ensure the synthetic fringe images with high SNR under ambient light. In this section, we will discuss how our proposed HDRFA can solve these problems.

### 2.1. Phase-shifting algorithms

In this research, a well-known four-step phase-shifting algorithm is adopted to retrieve fringe phase. The intensities of the four fringe images $H_i$ ($i=0, 1, 2, 3$) are written as

$$H_i(x,y) = I'(x,y) + I''(x,y)\cos[\Phi(x,y) + i \times \pi/2], \tag{1}$$

where $(x,y)$ is the pixel coordinate on the image plane of camera, $I'(x,y)$ is the average intensity, $I''(x,y)$ is the modulation intensity. Fringe phase $\Phi(x,y)$ can be calculated as follows:

$$\Phi(x,y) = \arctan\frac{H_3(x,y) - H_1(x,y)}{H_0(x,y) - H_2(x,y)}. \tag{2}$$

Eq. (2) gives the phase values between 0 and $2\pi$ only. Therefore, a phase-unwrapping algorithm is required to remove $2\pi$ discontinuities and to obtain a continuous phase map. Multi-frequency heterodyne principle [18,19] is used for full-field phase unwrapping, which is realized by projecting the fringe patterns with three different frequencies. This temporal unwrapping scheme can be used for measuring with complex objects without unwrapping problem in certain range.

From Eq. (1), the average intensity $I'$ and the modulation intensity $I''$ can be determined by

$$\begin{cases} I'(x,y) = \frac{H_0(x,y) + H_2(x,y)}{2} = \frac{H_1(x,y) + H_3(x,y)}{2} \\ I''(x,y) = \sqrt{[H_0(x,y) - H_2(x,y)]^2 + [H_1(x,y) - H_3(x,y)]^2}/2 \end{cases} \tag{3}$$

### 2.2. Analyses of fringe images on high-reflective surfaces

In above equations, $H_i$ is camera recorded fringe intensity. Here, we use $I_i^p (i = 0, 1, 2, 3)$ to express the intensity of the fringes from a digital projector as

$$I_i^p(x^p, y^p) = A\cos[2\pi x^p/\lambda + i \times \pi/2] + B, \tag{4}$$

where $(x^p, y^p)$ is the projector coordinate, $\lambda$ is the fringe pitch on the projector, A and B can be set by a computer to adjust the light intensity of a projected fringe. The fringe image actually acquired by the camera can be written as

$$\begin{aligned} H_i(x,y) &= kr(x,y)I_i^p(x^p, y^p) + kb_i(x,y) \\ &= kr(x,y)A\cos[2\pi x^p/\lambda + i \times \pi/2] + B + kb_i(x,y) \end{aligned} \tag{5}$$

where $k$ is the camera sensitivity, $r(x,y)$ is the surface reflectivity, and $b_i(x,y)$ is the ambient light reflected to the camera from the object surface.

The fringe modulation intensity can be expressed by

$$I''(x,y) = kr(x,y)A, \tag{6}$$

the average intensity is

$$I'(x,y) = k[r(x,y)B + b_i(x,y)]. \tag{7}$$

Fringe modulation (coefficient) is

$$\gamma(x,y) = \frac{I''(x,y)}{I'(x,y)} = \frac{r(x,y)A}{r(x,y)B + b_i(x,y)}. \tag{8}$$

Fringe signal SNR is proportional to the modulation intensity $I''$. A higher modulation intensity $I''(x,y)$ or high fringe modulation $\gamma(x,y)$ will always increase the phase measurement precision. When measuring high-reflective surfaces, surface reflectivity $r(x,y)$ has a large range. However, the dynamic range of the camera is limited. This causes CCD pixels to be saturated in higher reflectivity region and darker in lower region. Thus, phase values of saturated pixels cannot be calculated properly from fringe images and the precision of phase values in darker pixels is observably decreased due to a low SNR.

Eq. (6) shows that, to avoid fringe images from saturation and darker, camera sensitivity $k$, should be adjusted according to $r(x,y)$. This means that a larger $k$ should be used for a low $r(x,y)$ and a small $k$ for a high $r(x,y)$. However, as shown in Eq. (8), changing $k$ alone will not improve the fringe modulation and SNR of the fringe image. For larger $b_i(x,y)$, the right way to increase the value of $\gamma(x,y)$ is by enhancing the light intensity of the projected fringes, A and B, in Eq. (8).

### 2.3. HDRFA principle

The HDRFA aims at obtaining the optimal modulation intensity for high SNR of fringe image. It acquires a group of high-quality fringe images through selecting the camera exposure time and fringe intensity produced by projector. The HDRFA increases exposure time and the projected light intensity to obtain a higher