Journal of Visual Communication and Image Representation 50 (2018) 217–226

Contents lists available at ScienceDirect

Journal of Visual Communication and Image Representation

journal homepage: www.elsevier.com/locate/jvci

High dynamic range 3D shape determination based on automatic exposure selection☆

Li Rao, Feipeng Da*

School of Automation, Southeast University, Nanjing, Jiangsu 210096, China
Key Laboratory of Measurement and Control of Complex Systems of Engineering, Ministry of Education, Nanjing, Jiangsu 210096, China

ARTICLE INFO

Keywords:
3D measurement
Fringe projection
Random noises
High dynamic range
Multiple exposures

ABSTRACT

Traditional multi-exposure based high dynamic range fringe projection profilometry (FPP) technique is an effective method to obtain the 3D profiles of objects with drastic surface reflectivity variations. However, in this technique different exposure times often need to be selected empirically, making this method rather complicated. In this paper a completely automatic multi-exposure based FPP technique is proposed. No human intervention is required while applying the proposed method, which greatly simplify the whole reconstruction process. It is mathematically proved that once a pixel's modulation is larger than a threshold, the phase quality of this pixel can be considered satisfactory. This threshold can be used to guide the calculation of the needed exposure times. The software then automatically adjusts the camera's exposure time and captures the needed fringe images. Experiments show that with these captured images, the final reconstruction with a high dynamic range can be readily obtained.

1. Introduction

As a non-contacting optical technique, FPP is widely used in 3D shape determination due to its superiorities such as full-filed inspect, high resolution and accuracy. In FPP systems, one or more digital cameras are commonly used to capture several needed images. Due to the limited gray intensity range (256 levels for 8-bit cameras), the limited dynamic range of the cameras poses big challenges for FPP systems to obtain the 3D profile of objects with large surface reflectivity variations. For example, light reflected from specular surface, such as metallic material, will likely causes image saturation. Light rays reflected from the dark area of the measured object will lead to a weak image intensity, hence a low signal-to-noise ratio (SNR). In both circumstances, the phase cannot be calculated accurately and errors will appears in the final reconstructed 3D result. Therefore, saturation and low SNR in the captured images are considered the two important problems which affect the final reconstruction accuracy.

To conquer both problems brought about by low dynamic range of the digital camera, several high dynamic range (HDR) sensing techniques have been proposed. These methods can be mainly categorized into three categories:

1. **Hardware assisted technique.** In order to solve the image saturation problem, researchers apply special hardware into the FPP imaging system, such as light filters, spatial light modulator and so forth [1–6]. With the aid of polarizing filters or light modulator, the majority of the specular reflected light is filtered, thus the serious saturation can be effectively alleviated [1]. This technique works effectively if the measured object has high reflectivity variation such shiny metallic surfaces. However, the system setup can be rather complicated since one or more filters are needed. Further, because the filter drastically reduces the output light intensity of the projector and the incoming light of the camera, objects with diffuse and dark texture can be hardly measured. Instead of using filters in front of the camera or projector, Nayar et al. [4] design an optical mask and place it adjacent to the sensor array so that exposures of each pixel become different. This method can well enhance the dynamic range of the camera. However, it is not suitable for FPP systems.
2. **Scene adapted fringe projection algorithm.** In such algorithm, researchers focus on changing the projected fringe patterns instead of changing the camera parameters. Waddington and Kofman [7–10] develop a technique by adaptively adjusting the projected fringe pattern intensities, which makes the maximum input gray level to accommodate ambient light for saturation avoidance. A composite image is fused by raw fringe pattern images captured at different illuminations. However, similar to those methods by taking

---

☆ This paper has been recommended for acceptance by Zicheng Liu.

* Corresponding author at: School of Automation, Southeast University, Nanjing, Jiangsu 210096, China.
E-mail address: dafp@seu.edu.cn (F. Da).

https://doi.org/10.1016/j.jvcir.2017.12.003
Received 31 July 2017; Received in revised form 1 October 2017; Accepted 9 December 2017

multiple exposures, this technique also could be time-consuming. G. Babaie et al. [11] propose a recursive fringe pattern generation technique. By analyzing the captured image, the intensity of the projected pattern is adjusted pixel-by-pixel so that the high dynamic range fringe image can be obtained. Both Li et al. [12] and Lin et al. [13] propose very similar techniques in an effort to solve the saturation when measuring objects with a large surface reflectivity range. In their techniques, two relationships should be obtained: one is the pixel-to-pixel mapping between the projector and the camera, the other one is the intensity relationship between the designed pattern and the captured image. The original captured fringe images can be used as the guide to adaptively generate the new fringe patterns which can be used to avoid the image saturation.

3. **Multi-exposure based technique.** To enhance the dynamic range of imaging systems, an obvious approach is to sequentially capture multiple images of the same scene with different exposures [14–19]. The exposure for each image is controlled by varying the exposure time, the size of the aperture or the light sensitivity of the digital camera. Clearly, over exposed images will be saturated in the bright scene areas but the dark region can be well captured. In contrast, a lower exposure can effectively avoid saturation in bright regions but the details of the dark areas are likely lost. The complementary nature of these images allows one to combine them into a single high dynamic range image. This image fusion technique was applied firstly in Ref. [14,15]. Zhang et al. applied such dynamic range extending method in FPP in 2009 [16]. To the best of our knowledge, this kind of methods are the most effective among all methods which aim to solve problems caused by the limited dynamic range of digital cameras. However, the drawbacks of this technique are also obvious. One need to measure the object several times with multiple different exposures, which makes the measurement process laborious and complicated. Furthermore, the adjustments of the exposures are hard to precisely quantified. The gain of the digital camera and the aperture size should be adjust carefully as well.

In addition, in order to enhance the dynamic range of FPP systems, researchers also focus on other approaches which are not categorized into these three classes, such as considering color information of the real world [20–24] or applying special pattern coding or phase calculation method [25–30].

Among these introduced methods, the multi-exposure HDR technique has been proved to be effective but not efficient. Based on the idea of taking photos of the same scene under different exposure time, many researchers try to develop an automatic multi-exposure technique to boost the efficiency of this method. Ekstrand et al. [17] calculate the optimal exposure time automatically by analyzing the reflectivity of the measured object. However, only one exposure is used in this method, which is not enough if the measured object contains large texture variation. Jiang et al. [18] propose a multi-exposure method by simultaneously changing the camera parameters and the projected fringe intensity. In this method the human intervention can be well reduced. However, a parameter initialization process is required in this method. These parameters are not easy to accurately and suitably initialized if measuring an object with unknown surface reflectivity. Feng et al. [19] design an auto exposure algorithm by analyzing the reflectivity of the measured scene. In this proposed method, the exposure time is automatically determined with the aid of the intensity of the captured image. This exposure times still need to be manually determined in this method. Besides, to determine the exposure time according to the histogram of the captured intensity is not reliable once the measured object has a complex surface reflectivity variation.

In this paper we provide a totally automatic multi-exposure strategy. In this technique, the relationship between the noise-induced phase error and the captured fringe modulation is throughly analyzed. It is found that for a digital camera with a certain noise level, pixels whose modulations are larger than a proper value will have small enough phase error variance which can be ignored in the FPP system. This modulation value is set to be the modulation threshold. Since the modulation can be linearly changed by the exposure time, we can adjust the exposure time several times so that all pixels' modulation values are larger than this threshold. By analyzing the modulation and the intensity of the captured images, the exposure times can be automatically determined. Experiments show that the proposed method can well finish the reconstruction task of objects with complex reflectivity variation and on human intervention is required during the whole process.

The remainder of this paper is organised as follows: In Section 2, the automatic multi-exposure HDR strategy is introduced in detail. The validation experiments are provided in Section 3. The advantages and shortcomings of the proposed method are fully discussed in Sections 4 and 5 concludes this work.

2. Principle

2.1. Fringe pattern formation procedure

The simplified fringe pattern formation procedure of a FPP system is shown in Fig. 1. The fringe pattern I^s is generated by the computer and projected by the projector. Then the projected fringe pattern I^p is reflected by the measured objects and captured by the camera. Once the system is calibrated, the captured images I^c can be further used to obtain the 3D profile of the objects.

Normally, the computer generated standard pattern I^s has the following form:

$$I_i^s = a + b\cdot\cos(\theta + \delta_i), \tag{1}$$

where a,b, and θ are the background intensity, fringe modulation, and the phase map, respectively. δ_i is the phase step, $i = 1,2,\ldots,N$ and N is the total number of fringe images. Commonly, the relationship between the input and output signal of the projector can be expressed in a polynomial form:

$$I_i^p = \alpha_0 + \alpha_1\cdot I_i^s + f(I_i^s), \tag{2}$$

where α_0,α_1 are system coefficients and $f(I_i^s)$ denotes the high-order terms of I_i^s. Normally, $f(I_i^s)$ is far less than I_i^s. If the system nonlinearity is tackled by fringe pre-encoding technique [31], $f(I_i^s)$ can be ignored. Thus the projected fringe pattern can be simplified as

$$I_i^p = A + B\cos(\phi + \delta_i), \tag{3}$$

where A and B are the bias range and modulation, respectively. ϕ is the phase information in the projected image. The projected fringe patterns are then reflected by the measured object and the reflected light can be expressed as

$$I_i^o = r\cdot[I_i^p + a_1], \tag{4}$$

where a_1 is the ambient light which strikes on the object surface and r is the surface reflectivity. Finally, together with another ambient light a_2, the reflected fringe patterns are captured by digital cameras. The captured image is

$$I_i^c = \beta\cdot[I_i^o + a_2], \tag{5}$$

where β is the camera gain which is related to the exposure time, the

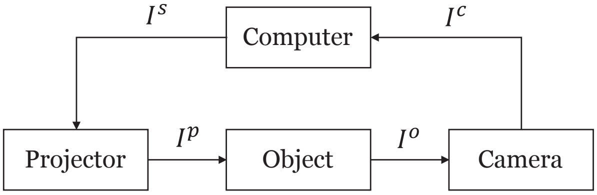

Fig. 1. Fringe pattern formation procedure.