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Technical note

Dynamics range enhancement in digital fringe projection technique

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ABSTRACT

In this paper a new approach to enhance the dynamic range of a fringe projection system for measuring 3D profile of objects with wide variation in their optical reflections is proposed. The high dynamic range fringe images are acquired by recursively controlling the intensity of the projection pattern at pixel level based on the feedback from the reflected images captured by the camera. A four step phase shifting algorithm combined with a quality guided algorithm is used to obtain the unwrapped phase map of the object from the acquired high dynamic range fringe images. Simulation and experimental results show that the proposed technique can accurately measure the 3D profile of objects with wide variation in their optical reflectivity.

1. Introduction

Limited dynamic range of conventional cameras causes difficulties in optical metrology of objects with wide variation in their optical reflectivity due to either their composition or form. For instance, metallic objects with steep slopes have a much higher level of intensity variation in their reflections compared to what can be captured by the 0–255 gray intensity range level of conventional cameras. As a result, reflected patterns taken by conventional cameras lose some information from such surfaces. Therefore, achieving a system with high dynamic range is a challenge in the field of optical metrology.

Acquiring 3D topography of objects is a very interesting and active field in both manufacturing and bio-medical imaging. One powerful technique to obtain a 3D profile of an object is the digital fringe projection technique [1,2]. A simple setup to apply fringe projection is to project interference fringes onto the object and observe the reflected pattern by a camera from another direction. The reflected pattern is a deformed fringe pattern, which has the height information of the object embedded in its phase distribution. Usually a fringe analysis technique, such as a phase-shifting algorithm, is needed in order to calculate the phase distribution of the reflected image [3]. However, as mentioned above, limited dynamic range of conventional cameras causes difficulties to obtain a correct phase distribution of patterns from objects with wide variation in their optical reflectivity. For example, Fig. 1(a) shows the image of a metallic ball from a fringe projection setup at low exposure time. Only areas with strong reflection toward the camera (tip of the metal ball) can provide measurable optical signals while light reaching the camera from other regions of the object is extremely weak. Thus, sufficient information from the illuminated object is not available to obtain surface topography of the object. As we increase the exposure time, Fig. 1(b), patterns reflected from sides of the ball with low reflection toward the camera become visible while pixels corresponding to areas with higher reflection toward the camera become saturated. Therefore the corresponding phase and intensity information of those areas (saturated pixels) are not measurable.

Several methods have been developed over the years to overcome the limited dynamic range problem of cameras. One proposed technique is to use polarizing filters [4]. This technique drastically reduces the overall intensity of the reflected pattern; therefore, it makes it difficult to obtain useful information from the darker areas of the scene. Another technique called 'High dynamics range scanning' was proposed by Yoshinori et al. [5], where a sequence of fringe images were taken from the surface at different exposure times. The images which were taken at low exposure times contained useful information from the areas of the surface with high reflectivity, while images taken at high exposure times contained useful information from the areas of the surface with low reflectivity. The final high dynamic range (HDR) image was reconstructed by choosing the brightest but not saturated corresponding pixel from each of the acquired images and combining them. The final HDR images were used for phase retrieving. This technique is very time consuming, and the sample under measurement needs

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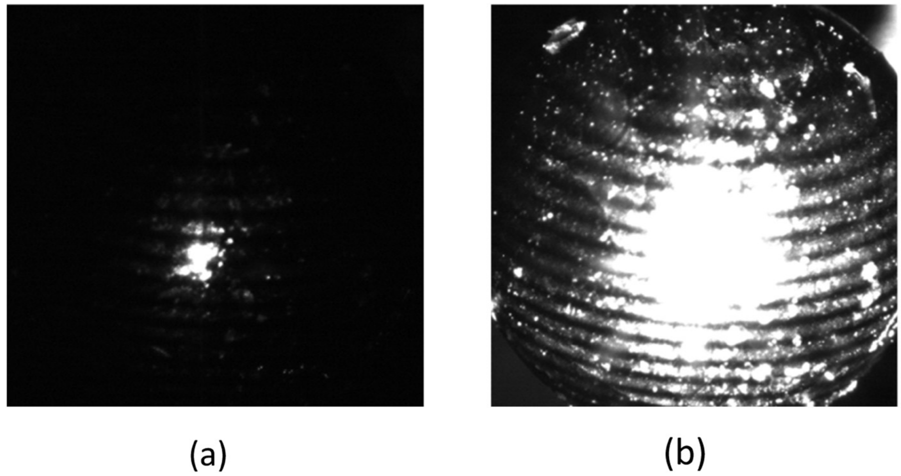

Fig. 1. (a) Reflected fringe pattern captured by the camera from the metallic ball with exposure time = 5 ms, and (b) reflected pattern of the same sample with exposure time = 1 s.

to be stationary. Recently an HDR imaging technique in fringe projection was proposed by Zhang et al. [6]. In this technique a high dynamic range image has been acquired by adjusting the intensity of some regions of the pattern using a DLP based on the feedback from the reflected pattern of the sample captured by the camera. In this technique they could improve the dynamic range of the fringe projection system with a single shot; however, since their enhancement technique is done in one-step; it cannot compensate for object with very wide variation of reflectivity. In addition, compensating in one-step could mistakenly decrease the intensity of pixels that have high intensity due to pixel bleeding effect and decrease the fringe contrast.

In this paper we are proposing a technique called 'spatially varying pixel intensity' (SVPI), which can enhance the dynamics range of a fringe projection system by recursively adjusting the intensity of the projected pattern at the pixel level. This technique improves the dynamic range of the imaging system with no physical modification in the fringe projection systems. In the experiment, to implement the concept, we used a metallic ball as the sample with a wide variation in its optical reflectivity. Afterward, we applied this technique to a series of solder bumps and measured the 3D profile of solder bumps designed for flip chip bonding. The measurement method of the proposed technique, the simulation and the experimental results will be discussed in this paper.

2. SVPI measurement method

The goal of SVPI technique is to control the irradiance of each pixel on the camera by repeatedly adjusting the intensity of the projection pattern at pixel level, therefore, a geometrical alignment is essential between the projector's and camera's pixels. To geometrically align the system, a checkerboard pattern is projected to the sample under the measurement and the reflection pattern is observed by the camera. Corners on the checkerboard pattern

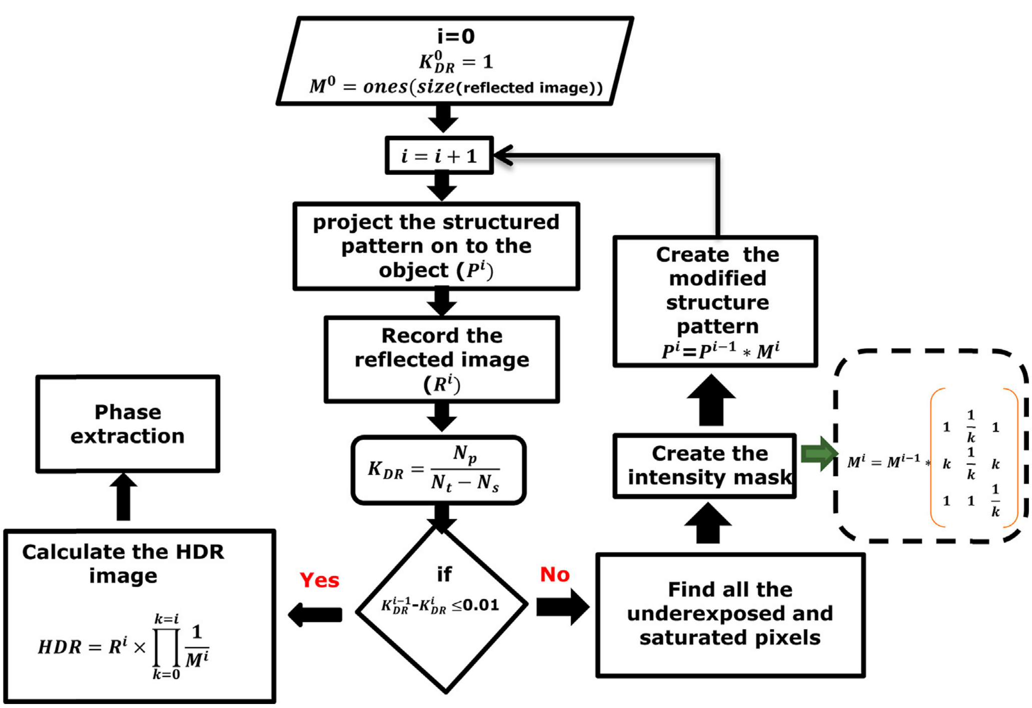

Fig. 2. Flowchart of dynamic range enhancement in fringe projection 3D profilometry based on spatially varying pixel intensity technique.