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Three-dimensional shape measurement technique for shiny surfaces by adaptive pixel-wise projection intensity adjustment

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ABSTRACT

Conventional methods based on analyses of the absolute gray levels of pixels in fringe pattern images are affected by the problems of image saturation, interreflection, and high sensitivity to noise when obtaining three-dimensional (3D) shape measurements of shiny surfaces. This study presents a robust, adaptive, and fast 3D shape measurement technique, which adaptively adjusts the pixel-wise intensity of the projected patterns, thus it avoids image saturation and has a high signal to noise ratio (SNR) during 3D shape measurement for shiny surfaces. Compared with previous time-consuming methods using multiple exposures and the projection of fringe patterns with multiple intensities, where a large number of fringe pattern images need to be captured, the proposed technique needs to capture far fewer pattern images for measurement. In addition, it can greatly reduce the time costs to obtain the optimal projection intensities by the fusion of uniform gray level patterns and coordinates mapping. Our experimental results demonstrate that the proposed technique can achieve highly accurate and efficient 3D shape measurement for shiny surfaces.

1. Introduction

Three-dimensional (3D) shape measurement is an important topic in computer vision, which has many different applications such as range sensoring, industrial inspection of manufactured parts, reverse engineering (digitization of complex, free-form surfaces), object recognition, 3D map building, biometrics, and the documentation of cultural artifacts [1,2]. Among the existing methods, structured light is one of the most widely used 3D shape measurement methods due to its superiorities of full-filed inspect, high resolution, and accuracy [3]. Typically, a structured light measurement system comprises a camera and a projector, which is modeled as an inverse camera in a similar manner to a classical stereo-vision system [4]. Some encoded patterns, which are also called structured light, are projected onto an object surface and images of the patterns distorted by the object surface are captured by a camera. After decoding the distorted patterns, the points in the camera and the projector image plane that share the same codewords are corresponded. The 3D coordinates of the object surface can be obtained by triangulation. The measured point cloud of the object can be further compared with the computer-aided design (CAD) model to evaluate the manufacturing quality.

The structured light method has many advantages, but it does not perform well if the objects have shiny surfaces due to their material or form. They have a much higher level of intensity variation in their reflections compared with that captured by the 0–255 gray-level intensity range of conventional cameras. Thus, the reflected patterns are either so bright that image saturation occurs, or so dark that they cannot be imaged clearly by cameras. In the structured light method, this means that the patterns cannot be correctly decoded, and thus the corresponding regions on the surface are not measurable.

Many methods have been developed for shiny surfaces. A method called high dynamic range (HDR) scanning was proposed by Zhang et al. [5], where a sequence of images captured at different exposures are combined as a single set of HDR images, i.e., phase-shifting images, by selecting the brightest unsaturated intensities at each pixel. The images taken at low exposure times contain useful information from regions on the surface with high reflectivity, whereas the images taken at high exposure times contain useful information from regions on the surface with low reflectivity. The final HDR images are used for phase retrieval. Moreover, Jiang et al. [6] proposed a method for capturing raw fringe images by simultaneously adjusting the exposure time and the projected light intensity, and synthesizing the HDR images by selecting pixels with the highest modulation intensity from the raw fringe images, so that a high SNR is obtained and the ambient light

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effect is minimized. The aperture of the camera lens and the camera exposure time can be adjusted easily, but the selection of the exposures is not quantified. In addition, in order to obtain high contrast HDR images, a large number of exposures are required, which is time consuming. To solve this problem, Jiang et al. [7] recently proposed a method that does not require the exposure to be changed. The fundamental idea is that as well as capturing regular fringe patterns, inverted fringe patterns are captured to complement the regular fringe patterns for phase retrieval. If not all of the regular fringe patterns are saturated, then inverted fringe patterns are used instead of the original saturated patterns for phase retrieval. Moreover, if all of the regular fringe patterns are saturated, both the original and inverted fringe patterns are used for phase computation to reduce the phase error. This method is not as robust as the previously proposed time-consuming methods using multiple exposures, but it can substantially increase the measurement quality for high-contrast surfaces in real time. Alternatively, Zhong et al. [8] proposed an enhanced phase measurement profilometry, which selects an optimal exposure time that is as large as possible as well as avoiding image saturation in regions of specular reflection during the phase shifting process. However, this technique using a single exposure time is limited to improve the signal to noise ratio (SNR) in the region of weak reflection. Thus, Feng et al. [9] used a histogram to predict one or more optimal exposure times based on the reflectivity distribution of the surface, thereby avoiding the blindness, i.e., in order to adapt to differences in surface reflectivity, previously proposed methods have taken as many exposure times as possible, or they relied on experience to select several exposure times. To address this time-consuming problem, Zhao et al. [10] proposed a very fast HDR fringe pattern projector with a frame rate of 700 Hz, which reduced the routine projecting time by 88%.

To handle objects with shiny surfaces, an alternative method involves projecting fringe patterns with multiple intensities. Waddington and Kofman [11] proposed a technique for projecting sinusoidal fringe patterns with the modified maximum input gray level (MIGL) to accommodate variable ambient illumination, which would otherwise cause image saturation and measurement errors during 3D shape measurement. However, this technique only adjusts the MIGL uniformly for the projector to avoid image saturation, which will reduce the SNR when measuring the surface regions with low reflectivity. Waddington and Kofman [12] then combined the MIGL reduction and pixel-by-pixel approaches, where by adaptively adjusting the projected fringe pattern intensities, a composite image is fused based on the raw fringe pattern images captured at different illuminations. However, similar to the methods using multiple exposures, this technique can also be time-consuming. Recently, the same team [13] developed an adaptive fringe pattern projection technique by locally modifying the MIGL in the projected fringe patterns according to the local reflectivity of the object surface being measured, which is better than simple adaptation using a single low MIGL for saturated regions.

Taking different approaches, a digital micromirror device camera [14] and several color invariants [15] are also used to eliminate the effects of high light on shiny surfaces. The color-invariant method is based on the dichromatic reflection model proposed by Shafer [16], where the color of a point is determined by the color of the object itself and the color of the light source. Diffuse reflection indicates the color information related to the object itself, whereas the specular reflection represents the color information for the light source [17]. However, this method is inevitably affected by the object itself if the object contains complex textures and multiple colors. In addition, the polarization method exploits the fact that polarized light will be scattered to depolarized light by a diffuse surface, whereas the polarized light remains polarized after specular reflection [18]. Thus, a pixelated polarizer array can be used to completely block the polarized light in the specular reflection so the shiny surfaces can be measured [19]. However, the polarizer must be carefully adjusted for the object without knowing its optical properties, which increases the complexity of the hardware.

Considering the inspection problems related to shiny surfaces, Lin et al. [20] developed an adaptive digital fringe projection technique for HDR 3D shape measurement. This technique can handle shiny surfaces and it improves the measurement accuracy by adaptively adjusting the pixel-wise intensity of the projected fringe patterns based on the camera's response function according to the reflectivity of the surface, as well as the illumination from ambient light and surface interreflections. This technique achieves good performance but the processing time required is disadvantageous because it takes more time to calculate the optimal projection intensities due to the large number of matrix inverse operations at the pixel level. Based on our previous study [20], we propose a method to reduce the time costs by the fusion of uniform gray level patterns and coordinates mapping. Monochromatic white and black stripe patterns are applied with a line-shifting method and sub-pixel edge detection in order to make the decoding procedure more robust, as well as improving the measurement resolution. Therefore, the proposed technique can obtain rapid measurements for objects with shiny surfaces, such as turbine blades, shafts, or glossy plastic parts.

The remainder of this paper is organized as follows. Section 2 explains the principle of the line-shifting method with sub-pixel edge detection. Section 3 describes the adaptive 3D shape measurement method. Section 4 presents the results of the experiments. We discuss the results and give our conclusions in Sections 5 and 6, respectively.

2. Line-shifting method with sub-pixel edge detection

For a structured light system, the encoding and decoding method is the most critical factor because it is used to find the correspondence between the camera and projector, which can affect the overall measurement performance in terms of the precision, point cloud density, and efficiency. Combining the Gray code with a phase-shifting method [21] and a multifrequency phase-shifting method [22] have been used widely for diffuse object measurement. Gühring et al. [23] noted that the phase-shifting method has several drawbacks: 1) the phase cannot be determined precisely when dealing with surfaces that have non-uniform albedo, especially when there are sharp changes from black to white; and 2) the intensity value at a pixel is influenced by those of its neighbors. In our previous study [20], we have established a novel mathematical model to comprehensively describe the factors that influence the gray level of a pixel from fringe pattern images, such as surface reflectivity, ambient light and surface interreflections. Our experiments show that these factors have a significant impact, especially for shiny surface measurements. Moreover, the nonlinearity of the structured light system including the gamma of the projector, surface reflectivity, ambient light and the response of the camera inevitably leads to the deviation of the captured fringe pattern from ideal sinusoidal waveforms and introduces an additional phase error. The main limitation of the phase-shifting method is that it bases on analyzing the absolute gray levels of a pixel from fringe pattern images, thereby leading to problems of image saturation, interreflection, and high sensitivity to noise. It should be noted that the Gray code pattern is much more reliable than sinusoidal phase-shifting fringe patterns, especially for shiny surfaces because only two gray levels need to be identified instead of the absolute gray level, which are coded as 0 and 1. Furthermore, the Gray code has a Hamming distance of one, so it is more robust against noise. Thus, Gühring et al. proposed a substitutional method called line shifting [24], which combines the Gray code with line shifting. Similar to phase shifting, a sequence of stripe patterns containing parallel lines are shifted and projected onto the object surface. In the present study, we describe a line-shifting method with sub-pixel edge detection in detail in the following section.