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Camera-independent saturation avoidance in measuring high-reflectivity-variation surfaces using pixel-wise composed images from projected patterns of different maximum gray level

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ABSTRACT

This paper presents a camera-independent method of avoiding image saturation in three-dimensional (3D) shape measurement of objects with a high range of reflectivity variation across the surface. Multiple sets of phased-shifted sinusoidal fringe patterns of different maximum gray level are first projected onto the object surface while images are captured of the fringe patterns. Then composite images are constructed pixel-by-pixel, by using at each pixel, only the highest intensity without saturation across a set of phase-shifted images. The composite images are then used in phase map and surface generation. Measurements of a surface with large range of reflectivity and high luminance variation across the surface demonstrated measurement accuracy improvements of 0.20 mm to 0.32 mm, using the composite-images based on multiple maximum projected gray levels, compared to measurement with the best single uniform maximum gray level across the projected patterns. This saturation avoidance method can be performed automatically independent of any camera-lens hardware and would permit a wide range of measurement applications in uncontrolled environments.

1. Introduction

Phase-shifting fringe-projection methods are commonly used for non-contacting three-dimensional (3D) surface-shape measurement, as they permit full-field measurement with high spatial resolution [1–6], providing 3D coordinates of a surface point for every camera pixel. A set of phase-shifted periodic varying-intensity fringe patterns is typically projected onto an object surface, images of the distorted patterns on the object surface are captured by a camera at an angle to the projector, and a phase map is computed from the camera images [7]. The phase map can then be used to determine correspondences between cameras in a multi-camera stereo system [8], or between a camera and projector in a single-camera-projector stereo system [9,10] before computation of object surface 3D coordinates based on a calibration of the stereo system. Alternatively, the object surface height or depth can be determined from the phase map, based on a phase-to-height mapping determined in a system calibration [11].

Under conditions of high object illuminance or high surface reflectivity, camera-image saturation can occur if the light input to the camera exceeds the maximum gray level of the camera sensor (255 for an 8-bit camera). The image intensities at affected pixels would be limited to this maximum level, and the resulting saturated image pixels of the captured deformed fringe patterns would lead to phase map errors, and ultimately surface-shape measurement errors. The level of light captured by the camera can be controlled by adjusting the camera aperture or exposure time to prevent saturation. The highest setting that avoids camera saturation would lead to the highest intensity modulation of the captured fringe pattern image and thus a higher signal-to-noise ratio (SNR) and higher measurement accuracy.

A single global aperture or exposure time setting works well for uniform illumination and surface reflectivity across the surface. However, high illumination or surface reflectivity in local surface regions would require a small aperture or exposure time setting to avoid saturation in the corresponding image regions, resulting in low intensity modulation in the remaining image regions. Approaches to handle specular light reflections that appear in isolated image regions use multiple camera viewpoints [12], multiple cameras, colour projections, and colour filters [13], and multiple projector directions [14] to form composite images without saturation, from the different acquired images. These approaches worked well for bright isolated regions but require additional complexity in hardware, system setup, and processing for image masking and registration to merge different surface regions.

Another approach avoids image saturation by capturing more than the minimum number of phase-shifted sinusoidal images,

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and calculating the phase at each pixel using only the unsaturated phase-shifted image pixels [15,16]. This approach is highly practical in not requiring complexity in hardware or system setup. However, the degree of saturation that can be avoided may be limited since the phase computation still requires the minimum number of phase-shifted images not saturated, and the remaining phase shifts employed may not be optimal.

High reflectivity variation across a surface presents a challenging problem, especially when the range of surface reflectivity is large. A single global aperture or exposure time that is lowered to avoid saturation in highly reflective regions, will unnecessarily reduce the captured intensity in the low reflectivity regions, and lower the intensity modulation and SNR in the captured images of the distorted fringe patterns. To address this problem, high dynamic range techniques have been applied whereby sets of images of phase-shifted fringe-patterns are captured at different camera exposure times, and the highest (brightest) unsaturated intensities from the images are combined pixel-by-pixel into composite phase-shifted images [17]. Alternatively, the highest intensity modulation has been used to create composite images [18]. In both approaches, the composite images would then be used to compute phase and surface height at each pixel. While these methods were able to avoid saturation, adjustment of exposure time may not be possible or practical for all off-the shelf camera hardware. One novel optical technique permits control of the camera exposure time at each pixel individually, for example, by employing a controllable optical attenuator [19,20]; however, additional optical and control hardware were required.

The above methods were able to avoid saturation for surfaces of high reflectivity variation across a surface using multiple camera-projector-object setup configurations or by adjusting the camera aperture or exposure time. However, the design of low-cost 3D shape-measurement systems especially for general consumer applications, would require a single simple hardware configuration, and may require low-cost off-the-shelf cameras that do not permit automated and remote means of aperture and exposure time adjustment. A camera-independent method that uses a single simple hardware configuration would therefore be desired in avoiding image saturation for surfaces of high reflectivity variation.

It has been shown that if projected fringe patterns are adjusted uniformly across the pattern by reducing the maximum input gray level (MIGL) to the projector, saturation can be avoided and measurement accuracy can thus be improved under conditions of increased ambient light for surfaces of generally uniform reflectivity and illumination [21]. While this offers a camera-independent approach to saturation avoidance for surfaces of generally uniform reflectivity and illumination [21], a pixel-by-pixel approach as done in Refs. [17–20] is needed to handle a high range of reflectivity variation across the surface. This paper presents a camera-independent method of avoiding saturation in measurement of surfaces with high range of reflectivity variation, by combining the MIGL reduction and pixel-by-pixel approaches, and thus creating composite images using unsaturated-pixel intensities acquired by projecting multiple sets of fringe patterns at different MIGL.

2. Method

2.1. Phase-shifting fringe projection in shape measurement

The camera-independent method of avoiding saturation in shape measurement of surfaces with high reflectivity variation was developed using a phase-shifting fringe-projection system (Fig. 1) that consists of a digital projector to project sinusoidal

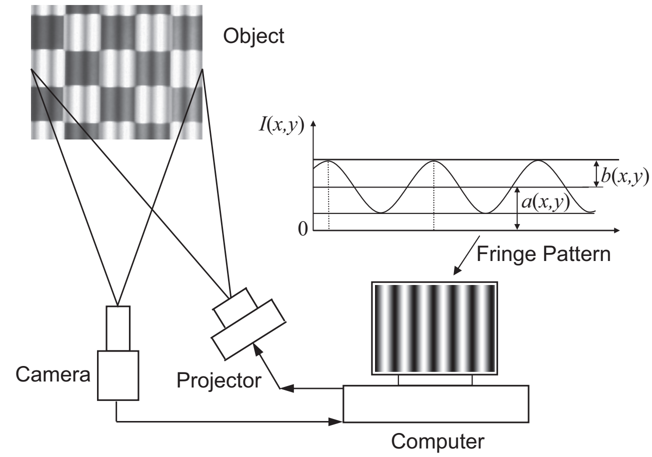

Fig. 1. Schematic diagram of phase-shifting fringe-projection system for 3D surface measurement.

phase-shifted fringe patterns onto an object surface, a camera at an angle to the projector to capture images of the fringe patterns that appear deformed on the object surface, and a computer to generate the fringe patterns and control and perform all processing.

The fringe pattern images I_i, for N phase-shifted patterns are given by the following equation [3]:

$$I_i(x,y) = a(x,y) + b(x,y)\cos\left[\varphi(x,y) + \delta_i\right], \quad i = 1,2,3,\ldots N, \tag{1}$$

where $a(x,y)$, $b(x,y)$, and $\varphi(x,y)$, which are unknown, are the background intensity, amplitude of modulation, and phase, respectively, at each image coordinate (x, y); and δ_i is the time varying phase shift:

$$\delta_i = \frac{2\pi\ i}{N}, \quad i = 1,2,3,\ldots N. \tag{2}$$

The phase map $\varphi(x,y)$, which contains the depth information, can be determined from the N phase-shifted images as follows:

$$\varphi(x,y) = -\arctan\frac{\sum_{i=1}^{N} I_i(x,y)\sin\ \delta_i}{\sum_{i=1}^{N} I(x,y)\cos\ \delta_i}. \tag{3}$$

The phase map $\varphi(x,y)$ is wrapped by 2π due to the arctangent function. A continuous phase map $\varphi_{obj}(x,y)$ can be obtained for the object surface by phase unwrapping [22,23] and similarly $\varphi_{ref}(x,y)$ obtained for a reference plane. The height (depth) $h(x,y)$ of an object surface at every image pixel (x,y), can then be determined from the phase difference [24,25]: $\Delta\varphi(x,y) = \varphi_{obj}(x,y) - \varphi_{ref}(x,y)$ by:

$$h(x,y) = K(x,y)\Delta\varphi(x,y), \tag{4}$$

where the phase-to-height map $K(x,y)$ is determined by an earlier calibration [11].

2.2. Influence of surface reflectivity in fringe pattern images

The effect of reflectivity of the surface being measured on the quality of surface shape measurement can be understood from the image intensity model incorporating reflected and ambient light [17]. The influence of different sources of luminance in capturing fringe pattern images by the camera is shown in Fig. 2, and described in the following equation:

$$I(x,y) = \alpha\ r(x,y)[a(x,y) + b(x,y)\cos(x,y) + a_r(x,y)] + \alpha\ a_e(x,y), \tag{5}$$

where $a(x,y)$ is the normalized background intensity, $b(x,y)$ is the amplitude of modulation, the projected fringe pattern is reflected