“Auto-exposure for 3D shape measurement with a digital fringe projection technique

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Abstract
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Phase shifting, auto exposure, three dimensional, digital fringe projection

Disciplines
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Comments
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Auto-exposure for 3-D shape measurement using a DLP projector

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ABSTRACT

Automatically adapting the camera exposure time is crucial for industrial applications where minimum human intervention is usually desirable. However, it is very challenging to realize such a capability for a conventional fringe projection system where only a finite increment of the exposure time is allowed due to its digital fringe generation nature. Our recent study on generating sinusoidal fringe patterns by properly defocusing binary ones permits the use of an arbitrary exposure time. This provides the potential to adapt the exposure time automatically. This paper will present the principle of an automatic exposure technique and show some experimental results.

Keywords: Phase shifting; auto exposure; three dimensional; defocusing; digital fringe projection.

1. INTRODUCTION

Automatically adapting the camera exposure based on the surface reflectivity of a measured object is crucial for industrial applications where minimum human intervention is usually desirable, and 3D shape measurement with digital fringe projection techniques is not an exception. However, it is very challenging to realize such a capability for a conventional fringe projection system.

There are basically five approaches to changing the intensity of the camera image in a fringe projection system: (1) Adjust projector aperture; (2) Adjust camera aperture; (3) Adjust projected fringe intensity; (4) Adjust camera gain; (5) Adjust camera exposure time. These methods can be classified into two categories: those requiring manual input (i.e., 1 & 2), and those that can be performed automatically. Typically, the best method for adjusting image exposure to acquire high-quality fringe patterns is to manually adjust one of the lens apertures. However, manual adjustments can cause undesired motion between system components that changes the system calibration. Therefore, development of a method that can automatically adjust image exposure is vital for high-precision 3D shape measurement. Adjusting the projected fringe pattern intensity is one of the options. This technique has been proposed to handle shiny object measurement. However, the fringe pattern is typically restricted to 8-bits (256 grayscale values). Moreover, changing the maximum grayscale value usually affects the signal-to-noise ratio (SNR) of the measurement since the fringe contrast changes. In general, sacrificing fringe contrast is not desirable. Likewise, it is also usually not desirable to change the camera gain since the SNR also changes accordingly.

Therefore, it seems that adjusting the camera exposure time is the best option. However, for conventional sinusoidal fringe patterns displayed on a digital-light-processing (DLP) projector, the camera exposure time cannot be arbitrarily chosen since the projector relies on time modulation for the generation of grayscale values between 0 and 255. To precisely capture the projected grayscale values, the projector and the camera must be precisely synchronized, and the smallest step to adjust the camera exposure time is its channel projection time (e.g., Δt = 8.33 ms for a 120 Hz projector). This step size is typically one to two orders of magnitude larger than the step size needed for practical exposure adjustment.

In this research, we propose to use the projector defocusing technique to circumvent the finite exposure time increment problem. This new technique for 3D shape measurement requires only binary structured patterns to realize conventional phase-shifting algorithms; the sinusoidal fringe patterns are realized by properly defocusing the projector. To increase the depth range of this technique, we will use binary patterns generated by optimal pulse width modulation (OPWM) rather than simple square waves. OPWM modifies a square wave pattern such that undesired harmonics that would decrease the fringe contrast is not desirable. Likewise, it is also usually not desirable to change the camera gain since the SNR also changes accordingly.

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This paper will present a 3D shape measurement system that could change its exposure time automatically according to the surface reflectivity of the measured object. The system uses a strategy that analyzes images of the object under uniform pure white light at several exposure times to determine the object’s surface reflectivity; the strategy then predicts an exposure time for the object that effectively controls the percentage of saturated pixels allowed in subsequent images. We have found that by controlling the exposure time automatically in this manner, high-quality 3D shape measurements can always be achieved for any type of diffuse object. This paper will present the principle of this technique in Section 2 and show some experimental results in Section 3. Section 4 will summarize this paper.

2. PRINCIPLES

2.1 Three-step phase-shifting technique

Phase-shifting methods are widely used in optical metrology because of their speed and accuracy. Over the years, numerous phase-shifting algorithms have been developed including three-step, four-step, double three-step, etc. In this research, we use a three-step phase-shifting algorithm to find the phase value. Three fringe images with a phase shift of $2\pi/3$ can be written as:

\[ I_1(x,y) = I'(x,y) + I''(x,y)\cos(\phi - 2\pi/3), \]
\[ I_2(x,y) = I'(x,y) + I''(x,y)\cos(\phi), \]
\[ I_3(x,y) = I'(x,y) + I''(x,y)\cos(\phi + 2\pi/3). \]

In Eqs. (1)-(3), $I'(x,y)$ is the average intensity, $I''(x,y)$ the intensity modulation, and $\phi(x,y)$ the phase to be computed. From these equations, we can obtain the phase

\[ \phi(x,y) = \tan^{-1}\left(\sqrt{3}(I_1 - I_3)/(2I_2 - I_1 - I_3)\right). \] (4)

This equation provides the $\phi(x,y)$ value ranging from $-\pi$ to $+\pi$ with $2\pi$ discontinuities, which is usually called the wrapped phase. The $2\pi$ phase discontinuities can be removed to obtain a continuous phase map by adopting a phase unwrapping algorithm. Once the continuous phase map is obtained, the 3D shape can be recovered from the phase through calibration.

2.2 Digital-light-processing (DLP) fundamentals

The core of the digital-light-processing projector is the digital micro-mirror device (DMD). Each micro-mirror can rotate between $+\theta_L$ (ON) and $-\theta_L$ (OFF). The grayscale value of each pixel is realized by controlling the ON time ratio: 0% ON time represents 0, 50% ON time means 128, and 100% ON time is 255. Therefore, a DLP projector produces a grayscale value by time modulation.

We have carried out a simple experiment to verify the time modulation behavior of the DLP projector used in our system, the Logic PD DLP LightCommander development kit. In this experiment, we connected a photodiode (Model: Thorlabs FDS100) with a resistor (30 kΩ) to sense the output light of the projector. An oscilloscope (Tektronix TDS2024B) was used to monitor the voltage of the photodiode system as the projector projected uniform grayscale images at values of 255, 128, 64, and 0. Figure 1 shows the resulting oscilloscope output. In Figures 1(a) and 1(d), the light level from the projector appears relatively constant at a high level and a low level, respectively. At a grayscale value of 128, as shown in Fig. 1(b), the light level alternates between low and high, remaining at each level for approximately equal amounts of time. At a grayscale value of 64, the light level again alternates between the two levels, but it only jumps to the high level for about one quarter of the time. These experiments showed that if the projected image contains grayscale values between 0 and 255, as sinusoidal fringe patterns do, the whole projection period needs to be captured to image the correct pattern. Therefore, to correctly capture a conventional sinusoidal fringe pattern projected by a 60 Hz DLP projector for 3D shape measurement, the camera exposure time must be a multiple of 1/60 second. This is certainly not desirable when the flexibility of controlling exposure time is required. In contrast, if the projected image contains only 0s and/or 255s, each DLP micro-mirror remains stationary during refreshing, and thus any partial time segment can represent the whole projected signal. Therefore, an arbitrary camera exposure time can be utilized to capture the projected image, as has been previously verified.
2.3 Sinusoidal fringe pattern generation by defocusing

As aforementioned, if the DMD is fed with 0 or 255, it will retain its status (without flipping ON/OFF) during the period of channel projection. Therefore, if binary (0s and 255s) instead of sinusoidal structured patterns are used, it permits the use of an arbitrary exposure time for the camera. However, to perform 3D shape measurement with a phase-shifting method, sinusoidal fringe patterns are required.

Our recent study showed that by properly defocusing a binary structured pattern, a pseudo-sinusoidal one can be generated,1 which is similar to the Ronchi grating defocusing method proposed by Su et al.10 Figure 2 shows some typical results when the projector is defocused to different degrees while the camera is in focus. The pattern employed here is a basic set of black-and-white stripes referred to as a squared binary pattern (SBM). This figure shows that as the projector becomes increasingly defocused, the binary structured pattern becomes increasingly distorted. Fig. 2(a) shows the result when the projector is in focus: clear binary structures on the image. As the degree of defocusing increases, the binary structures become less and less clear, and the sinusoidal ones become more and more obvious. However, if the projector is defocused too much, the sinusoidal structures start diminishing, as indicated in Fig. 2(f). This experiment indicates that a pseudo-sinusoidal fringe pattern can indeed be generated by properly defocusing a binary structured pattern.

However, this seemingly sinusoidal fringe pattern retains some of its binary structure in the form of harmonics beyond the fundamental sinusoidal frequency. Some of these harmonics induce errors in the results that limit the depth range for accurate 3D measurement. An alternative approach to the defocusing technique uses fringe patterns generated by optimal pulse width modulation (OPWM). OPWM produces binary fringe patterns by selectively removing regions of the square wave of SBM that would generate the undesired harmonics after defocusing.4 This technique is often used in the field of electrical engineering to generate sinusoidal waveforms.11 Figure 3 shows a SBM pattern in comparison to an OPWM pattern, illustrating the shifting of columns that takes place during the removal of selected harmonics. Indeed, Figure 3(b)
appears more sinusoidal even prior to defocusing. Therefore, defocused OPWM patterns offer a binary alternative to sinusoidal patterns for phase-shifting while still allowing an arbitrary camera exposure time.

\[
I(x,y;t) = \gamma [L^a + \rho L^0 + \rho L^p] \times t + I^c. \tag{5}
\]

If the projected light \(L^p\) is intense enough, we can assume that \(L^a\) and \(L^0\) are negligible in comparison. We also know that for a given pixel, \(\gamma\) and \(\rho\) are constants. If we then also assume that the LED light is approximately constant over time, \(L^p\) is also a constant for each pixel. (Since binary patterns are projected, the micromirrors will be stationary as explained in Sec. 2.2.) Therefore, Eq. (5) becomes

\[
I(x,y;t) = \gamma \rho L^p \times t + I^c = k(x,y) \times t + c(x,y). \tag{6}
\]

For a stationary object, \(k(x,y)\) can be determined by capturing a set of images of the object with different exposure times and fitting a line to the intensities of each pixel with linear regression. Since \(\gamma\) and \(L^p\) are known and controlled, \(k(x,y)\) can be used to determine the approximate surface reflectivity \(\rho(x,y)\) for the object at each imaged pixel. Theoretically, only two images are required to determine \(\rho(x,y)\). However, because of noise, more images are desirable to increase the accuracy of the determination.

With the surface reflectivity \(\rho(x,y)\) now well-approximated, a strategy can be formed for selecting the optimum exposure time for each pixel \(t(x,y)\). Several images can then be taken, encompassing the range of \(t(x,y)\) values determined, and the images blended together to yield data of maximized quality for 3D computations.\(^{12}\) However, in practice, a single exposure time for the whole image is desirable to speed up the measurement procedures. The remainder of the framework must outline criteria for selecting this single, optimum exposure time.

In optimizing image exposure for 3D computations, it is crucial to avoid saturating the camera sensor in areas of high surface reflectivity without sacrificing fringe contrast in areas of low surface reflectivity.\(^{12}\) In other words, a trade-off must be made between overexposing the brightest areas of a subject and losing the fringes in the darkest areas of a subject in shadow. Therefore, the best approach selects a single exposure time that results in an image where the subject's high-reflectivity regions come as close to saturated as possible without actually becoming saturated. This is the operating principle of this proposed automatic exposure method.

In the proposed method, the measured reflectivity values of the subject are first isolated from the background and then sorted from greatest to least as \(\rho_1 \geq \rho_2 \geq \cdots \geq \rho_{n-1} \geq \rho_n\), where \(n\) is the total number of reflectivity values belonging to the subject. An index \(m\) into this ordered set is selected according to the criteria

\[
m = \text{Round}(n \times P), \tag{7}
\]
where $P$ is a chosen percentage. The reflectivity value at this index, $\rho_m$, is inserted into Eq. (6) and the intensity value output of Eq. (6) set to $I_{\text{max}}$, a maximum desired pixel intensity value for the final image. This yields

$$I_{\text{max}} = \gamma \rho_m L^p \times t + c_m. \quad (8)$$

Here $c_m$ is the intercept value from the linear regression solution for the pixel with reflectivity $\rho_m$. Since $c_m \ll I_{\text{max}}$, we can assume the effect of $c_m$ to be negligible. Therefore, solving for $t$, we have the prediction equation

$$t = \frac{I_{\text{max}}}{\gamma \rho_m L^p}. \quad (9)$$

The predicted exposure time $t$, used in conjunction with the same values of $\gamma$ and $L^p$ used in its determination, yields an image with approximately the upper $P$ percentage of subject pixels having intensities $I \geq I_{\text{max}}$. When $I_{\text{max}}$ is set to the saturation point of the camera sensor and $P$ is chosen small enough to prevent data loss from saturation, Eq. (9) yields the optimum exposure time for 3D measurement.

3. EXPERIMENTS

We developed the 3D measurement system shown in Figure 4 to verify the proposed technique. It includes a high-speed CMOS camera (Phantom v9.1) and an LED DLP projector (Logic PD DLP LightCommander). Both projector and camera are outfitted with the AF Nikkor 50 mm focal length lens adjusted to $f/1.8$ to minimize the effect of ambient light on the results. The projector has a resolution of $1024 \times 768$, and the LEDs are set at 100% brightness to further minimize the effect of ambient light. The camera resolution is adjusted to $1152 \times 1152$, and the gain is set at 1.00 to avoid amplifying the noise. The camera is triggered with a 5 V square pulse from a function generator (Tektronix AFG 3022B) triggered off the projector sync signal (this serves to amplify the projector signal).

![Fig. 4. Photograph of the test system.](image)

We verify the exposure time optimization procedure by testing on it a diffuse white sculpture as shown in Figure 5. To determine the reflectivity values for the sculpture, it was photographed by the system camera against a black background under uniform pure white (255, 255, 255) illumination from the system projector.

Photographs were taken at exposure times in increments of 50 $\mu$s from 50 $\mu$s to 700 $\mu$s. Figures 5(a) through 5(d) contain four representative pictures from this set. From this image set, an optimized exposure time of 303 $\mu$s was predicted for the sculpture. Figure 5(e) shows the statue at its optimized exposure time again illuminated by the projector with pure white light against a black background. This image appears to have the desired level of exposure for 3D measurement. The sculpture’s face is not overexposed, although some details are lost in shadow, no facial details are underexposed.

To verify that this exposure time did indeed lead to good 3D measurement results for the sculpture, the three-step phase-shifting algorithm was used to obtain 3D data with the predicted exposure time of 303 $\mu$s. OPWM structured patterns were used to increase the measurement depth range, and the absolute phase maps were obtained through the multiwavelength technique. Figure 5(f) shows a representative fringe image using the optimal exposure time. This figure shows that the
Fig. 5. The exposure time optimization process for a diffuse white sculpture. Reflectivity analysis images at exposure times of (a) 50 μs; (b) 150 μs; (c) 450 μs; (d) 700 μs. (e) The sculpture at its predicted exposure time of 303 μs. (f) Representative fringe image for \( t = 303 \mu s \). (g)-(h) 3D measurement results for \( t = 303 \mu s \).

Fringe image has a good SNR for the sculpture’s face, and this results in the 3D measurements of good quality shown in Figures 5(g) and 5(h).

To further verify the proposed automatic exposure method, we test it on another sculpture, shown in comparison with the first in Figure 6. This diffuse brown sculpture has a much lower average reflectivity value than the white one, thus it will require a much longer exposure time. Indeed, the automatic exposure algorithm predicted an exposure time of 1083 μs for this second sculpture when it was photographed under the same conditions as the first.

Fig. 6. Photograph of the two sculptures used for verification.
Figure 7 presents the representative fringe images and their corresponding 3D measurement results for the two sculptures at these two predicted optimal exposure times (303 μs for the white sculpture and 1083 μs for the brown sculpture). Figures 7(a) and 7(b) are fringe images taken at \( t = 303 \mu s \), and Figures 7(e) and 7(f) are their resulting 3D measurements. Compared to the high SNR and correct exposure of the white sculpture fringe image, the brown sculpture’s fringe image has very low SNR and exhibits underexposed areas. This leads to the very poor 3D measurement results for the brown sculpture shown in Figure 7(f). Figures 7(c) and 7(d) are fringe images captured at \( t = 1083 \mu s \), and Figures 7(g) and 7(h) show their corresponding 3D measurement results. Here, the white sculpture is very overexposed, while the brown sculpture has the correct exposure and good fringe SNR. The overexposure leads to incorrect measurement areas (depicted as large holes) in the 3D measurement data shown in Figure 7(g). However, as expected, the 3D results for the brown sculpture in Figure 7(h) are of high quality. This illustrates that the 3D results for each sculpture are of good quality when the data is taken at their predicted optimal exposure time and are of very poor quality when the data is taken at a vastly different exposure time.

These experiments have demonstrated that the proposed automatic exposure time framework performs well. The framework is able to automatically determine the appropriate exposure time for high-quality 3D shape measurement, successfully preventing the drastic errors caused by gross over- or underexposure in the fringe images.

4. CONCLUSIONS

This paper has presented a framework for automatically adjusting image exposure to achieve high-quality 3D measurements on a digital fringe projection system. The use of binary structured pattern defocusing techniques permits the system to have an arbitrary exposure time which can be used to change the image intensity automatically and without sacrificing a good fringe signal-to-noise ratio. A series of images of the subject at increasing exposure times can be used to predict the correct
exposure time for the subject. Experiments have shown that this predicted exposure time leads to good quality 3D results for the subject, avoiding the loss of data caused by over- and underexposure of the fringe images. This technique reduces the amount of human intervention required for 3D measurement with digital fringe projection, allowing the system to be robust to changing subjects. Future work will focus on increasing the dynamic range of this technique.

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