General solution for high dynamic range three-dimensional shape measurement using the fringe projection technique

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A R T I C L E   I N F O

Article history:
Received 26 September 2013
Received in revised form
24 February 2014
Accepted 9 March 2014
Available online 4 April 2014

Keywords:
Fringe Projection
High dynamic range
Specular Reflection
Shiny surface
Polarization

A B S T R A C T

This paper presents a general solution for realizing high dynamic range three-dimensional (3-D) shape measurement based on fringe projection. Three concrete techniques are involved in the solution for measuring object with large range of reflectivity (LRR) or one with shiny specular surface. For the first technique, the measured surface reflectivities are sub-divided into several groups based on its histogram distribution, then the optimal exposure time for each group can be predicted adaptively so that the bright as well as dark areas on the measured surface are able to be handled without any compromise. Phase-shifted images are then captured at the calculated exposure times and a composite phase-shifted image is generated by extracting the optimally exposed pixels in the raw fringes images. For the second technique, it is proposed by introducing two orthogonal polarizers which are placed separately in front of the camera and projector into the first technique and the third one is developed by combining the second technique with the strategy of properly altering the angle between the transmission axes of the two polarizers. Experimental results show that the first technique can effectively improve the measurement accuracy of diffuse objects with LRR, the second one is capable of measuring object with weak specular reflection (WSR: e.g. shiny plastic surface) and the third can inspect surface with strong specular reflection (SSR: e.g. highlight on aluminum alloy) precisely. Further, more complex scene, such as the one with LRR and WSR, or even the one simultaneously involving LRR, WSR and SSR, can be measured accurately by the proposed solution.

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1. Introduction

The 3-D shape measuring technique is playing an increasingly important role in many fields, such as manufacturing industry, rapid reverse engineering, entertainment and biomedical science. Conventionally, coordinate measuring machine is always utilized to achieve geometric shape measurement for its advantage of high precision and due to its surface-contact nature, it can measure object with shiny or dark surface. However, it is inappropriate for this technique to handle soft object since the surface contact may destruct the measured contour. Besides, its measurement speed is very slow which usually results in low efficiency.

In contrast, optics-based 3-D profilometry can measure very fast and avoid the surface contact [1,2]. Optical approaches include fringe projection, laser range scanning, binocular stereo vision and so on. Among these techniques, fringe projection is one of the most widely used 3-D shape measuring technique due to its superiorities of full-filed inspect, high resolution and accuracy but, this method is not trouble-free: (1) for the surface with LRR, it is quite difficult to ensure high quality fringes being captured on both bright and dark portion of measured surface simultaneously, since the reflected light has a large dynamic range; (2) the commonly used fringe projection methods are generally proposed with an implicit assumption that the measured object is of diffuse surface not the specular one [3,4]. This is because the light reflected by specular surface is so intense that it always leads to camera sensor being saturated which means that the fringes modulated by the highlight area cannot be correctly captured.

Thus, to measure object with LRR, Zhang et al. [5] proposed a high dynamic range scanning technique in which fringes with good image quality is generated by synthesizing a sequence of fringe images captured at different exposure times. Since the used exposure time is subjectively selected, it lacks quantitative manner to determine the proper exposure time. Besides, in order to obtain high contrast fringes, a large number of exposures are required, which is not very convenient. Then, Ekstrand et al. [6] presented an auto-exposure technique in which the required exposure time

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http://dx.doi.org/10.1016/j.optlaseng.2014.03.003
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can be predicted automatically according to the reflectivity of measured object surface. This method reduces the human intervention and improves the intelligence of the 3-D shape measurement system but, the predicted exposure time is obtained on the basis of the intensity of the brightest region on the object, thus this unique exposure usually cannot meet the requirements of some dark parts in the same measured scene. Besides, Liu et al. [7] also introduced an approach that permits dual-camera structured light illumination system to tackle object surface with LRR. 256 pieces of even white image with incremental gray level from 0 to 255 are required to be casted onto measured object for creating mask image used in their method; the whole procedure would be very time-consuming. In addition, Waddington and Kofman [8,9] developed a method of projecting fringe patterns with modified output light intensity to accommodate ambient light for saturation avoidance and a composite image is fused by raw fringe images captured at different illuminations. The contrast of the fringes, however, may be reduced when the projected light intensity decreases.

To handle object with high-reflective shiny surface, methods in Refs. [10–12] used polarizing filters to eliminate the effect of highlights by changing the angle between the transmission axes of the polarizers. The intense specular light is effectively removed; however, at the expense of reduction of captured intensity for the whole image, may result in low signal-to-noise ratio. Jiang et al. [13,14] proposed a method of capturing raw fringe images by simultaneously changing the camera exposure time and the projected light intensity, and forming a composite fringe image by selecting pixels with the largest modulation from the raw images. As fringes of high signal-to-noise ratio were generated, this method could achieve precise measurement of shiny surface but, the determination of the initial values of the used parameters may not be very convenient when inspecting an unknown scenario since the initial values cannot be obtained adaptively according to the measured scene. Generally speaking, as all of the mentioned techniques were presented to deal with a specific issue, e.g. LRR or specular highlight, they may be potentially problematic when measuring the scene simultaneously having these two issues.

The goal of this paper is to present a general solution to achieve high dynamic range 3-D shape measurement. It is a solution that can be universally applied to solve the measurement problems ranging from LRR to specular reflection. There are three techniques involved in the solution. The first technique, named Technique I, is introduced for measuring surface with LRR. In this technique, the reflectivity distribution of measured scene is firstly obtained by using the method of histogram and, one or more optimal exposure times are predicted on the basis of the deduced reflectivity distribution. Then raw phase-shift images are captured at the predicted exposure times and a synthesized phase-shift image is formed by selecting pixels in raw images with optimal exposure. For measuring object with specular reflection, we classify this kind of reflection into two categories: weak specular reflection (WSR) and strong specular reflection (SSR). The Technique II, which is developed to handle the object with WSR, introduces two perpendicular polarizers into Technique I to remove the effect of highlight and use the merit of Technique I to ensure high contrast fringes. Besides, scenes with LRR and WSR can also be measured by this technique. Last but not least, to tackle the surface with SSR, the third technique named Technique III is proposed. It is built on the basis of Technique II and a strategy that the angle of the polarizers is slightly adjusted away from 90°. Further, not only does the Technique III can measure surface with SSR, but also it can cope with more complex scene simultaneously involving surfaces with LRR, WSR and SSR. Our experimental results show the presented solution is valid and practical. In addition, compared to traditional method, the proposed solution can improve measurement precision by an order of magnitude.

Section 2 details the principles of the proposed solution. Section 3 presents some of experimental results and discusses the versatility of the solution. Section 4 summarizes this paper.

2. Principle

2.1. N-step phase-shifting algorithm and temporal phase-unwrapping algorithm

The N-step phase-shifting algorithm is extensively applied in fringe projection profilometry due to its advantageous features including pixel by pixel phase recovery and high measurement accuracy. The intensity of the fringe image with a phase shift \(2\pi / N\) can be written as follows:

\[
I(x, y) = A(x, y) + B(x, y) \cos \left[\phi(x, y) + 2\pi n / N\right]
\]

where \(n\) denotes phase-shift index, \(N\) the total number of phase shift and \((x, y)\) the pixel coordinate. According to Eq. (1), the phase \(\phi(x, y)\) can be solved by

\[
\phi(x, y) = \tan^{-1} \frac{\sum_{n=1}^{N} I_h(x, y) \sin(2\pi n / N)}{\sum_{n=1}^{N} I_h(x, y) \cos(2\pi n / N)}
\]

The average intensity \(A(x, y)\) and intensity modulation \(B(x, y)\) can be determined by

\[
A(x, y) = \frac{\sum_{n=1}^{N} I_h(x, y)}{N}
\]

\[
B(x, y) = \frac{1}{N} \left(\sqrt{\sum_{n=1}^{N} I_h(x, y) \sin(2\pi n / N)}^2 + \left|\sum_{n=1}^{N} I_h(x, y) \cos(2\pi n / N)\right|^2\right)
\]

The calculated phase value \(\phi_0(x, y)\) from Eq. (2) ranges from \(-\pi\) to \(+\pi\). If the projected fringe patterns contain only one sinusoidal fringe, there is no need to unwrap the phase. Attributed to the noise effect from measurement system and surroundings, however, the derived phase will be of low accuracy. Thus, high-frequency patterns with multiple periods of sinusoidal fringes are usually employed to obtain a more accurate phase map. As multi-sinusoidal fringes images are introduced, it is necessary to remove the \(2\pi\) discontinuities of the wrapped phase for achieving continuous phase distribution. In this paper, two-frequency temporal phase-unwrapping algorithm is used to remove the phase ambiguity:

\[
\Phi(x, y) = \phi(x, y) + 2\pi N
\]

\[
N = \text{Round}\left(\frac{K \phi(x, y) - \phi(x, y)}{2\pi}\right)
\]

where \(\Phi(x, y)\) is the unwrapped phase, \(\phi(x, y)\) is the wrapped phase derived from high-frequency sinusoidal fringes and \(\Phi(x, y)\) is the phase from low-frequency fringes. \(\text{Round}\) ( ) is to get the nearest integer. The coefficient \(K\) satisfies the relationship \(\phi^h = K \phi^f\), where \(\phi^h\) is the frequency of \(\phi(x, y)\) and \(\phi^f\) the frequency of \(\phi(x, y)\). In this paper, we assume that the resolution of projector is \(W \times H\) and the projected fringe patterns are vertical, the low-frequency means its wavelength \(\lambda^L = W\). After the phase being unwrapped, it can be converted to 3-D coordinate if the measurement system is calibrated [16].

2.2. Technique I: adaptive multi-exposure technique

The first technique included in the proposed solution, is developed to solve the measuring issue arose from diffuse surface
with LRR. Here, the ‘adaptive’ means that based on the reflection character of measured object, the technique is able to predict different optimal exposure time for surface with different reflectivity. Without loss of generality, we assume that the reflectivity would be uniform for surface of the same material. According to the 3-D profilometry based on fringe projection, the schematic diagram is illustrated in Fig. 1, where \( I^p \) is the projected intensity and \( \alpha \) is the surface reflectivity. It can be seen that the captured intensity is composed of three components: (1) the reflected projection light \( \alpha I^p \); (2) the reflected ambient light \( \alpha \beta_1 \); and (3) the ambient light entering directly into the camera \( \beta_2 \). Thus, when the projected light is uniformly bright \((255, 255, 255)\), the intensity \( I \) will be constant. This assumption holds for most digital cameras with a good linear photometric response [17]. From Eq. (7), if the measuring environment is dark enough or the reflected ambient light \( \alpha \beta_1 \) and the captured image \( I^0 \) are linear, which means that the variation of \( I^0 \) can be directly used to represent the variation of reflectivity. To obtain the distribution of \( I^0 \), we calculate the histogram of \( I^0 \), in which the horizontal axis shows the variation of intensity of \( I^0 \) and vertical one depicts the amount of pixels in that particular \( I^0 \). An example of histogram is shown in Fig. 2. The region of light green represents the whole variation range of the captured intensity \( I^0 \). By the proposed method, the whole large variation range is further divided into several clusters composed of pixels varying in small range of \( I^0 \). As shown in Fig. 2, each cluster is distinguished by a significant peak together with its surrounded two significant valleys and along the positive direction of \( I^0 \), the clusters are marked from 1 to \( m \), which is the total number of determined clusters. Since the pixels within a certain cluster have similar reflectivity, a single exposure would be sufficient for a single cluster. To predict an exposure time that is able to entirely cover each cluster, we choose the value of \( I^0 \) corresponding to the significant valley on the right side of each cluster to calculate the exposure time. For example, in Fig. 2, \( I^0_{c1} \) is used to compute optimal exposure time for cluster 1, \( I^0_{c2} \) for cluster 2 and so on.

To calculate optimal exposure time for each cluster, Eq. (13) has been changed into

\[
t_{\text{opt}} = \frac{I_{\text{ideal}}}{s_\alpha I^p}
\]

(14)

where \( I_{\text{opt}} \) is the horizontal axis coordinate of the significant valley on the right side of cluster \( i \) \((i = 1, 2, \ldots, m)\), and \( t_{\text{opt}} \) is the calculated optimal exposure time for cluster \( i \). Since the needed exposure times have been predicted, we then capture every phase-shift image at these exposure times.

To select the optimally exposed pixels from the raw fringe images, a set of masks \( M_i(x, y) \) \((i = 1, 2, \ldots, m)\) are created. Since cluster \( i \) is composed of pixels satisfying \((x, y)\left(I_{(i-1)} < I_0(x, y) \leq I_0(x, y)\right)\) as shown in Fig. 2, the masks can be developed by

\[
M_i(x, y) = \begin{cases} 
1, & \text{if } I_{(i-1)} < I_0(x, y) \leq I_0 \\
0, & \text{otherwise}
\end{cases}
\]

(15)

In the mask \( M_i \), pixels within cluster \( i \) will be retained because their mask values are set equal to 1 and a composite fringe image

\[
\text{sat}^p = \frac{I_0}{I^0}
\]

(12)

Since Eq. (12) shows the computation of the product term \( \text{sat}^p \), we substitute it into Eq. (10). Finally, the optimal exposure time \( t_{\text{opt}} \) can be expressed as

\[
t_{\text{opt}} = \frac{I_{\text{ideal}}}{I_0}
\]

(13)

Eq. (13) shows that the optimal exposure time can be readily acquired once the exposure time \( t_0 \) and the image \( I_0 \) are obtained. However, by Eq. (13), each pixel will correspond to an optimal exposure time. It is impossible to measure object at every acquired exposure time. Thus a strategy to determine the needed optimal exposure times follows.

By experiments we find that only several exposure times would be adequate for general measured scene due to the fact that a single exposure time can provide enough exposure for surface with a small variation range of reflectivity. So, if large variation range of reflectivity can be divided into several small variation ranges, the needed exposure times can be readily obtained. To achieve the variation range of reflectivity, a uniform bright image \((255, 255, 255)\) is projected onto measured scene and then set an exposure time \( t_0 \) to capture image \( I_0 \). According to Eq. (11), the reflectivity \( \alpha \) and the captured image \( I_0 \) are linear, which means that the variation of \( I_0 \) can be directly used to represent the variation of reflectivity. To obtain the distribution of \( I_0 \), we calculate the histogram of \( I_0 \), in which the horizontal axis shows the variation of intensity of \( I_0 \) and vertical one depicts the amount of pixels in that particular \( I_0 \). An example of histogram is shown in Fig. 2. The region of light green represents the whole variation range of the captured intensity \( I_0 \). By the proposed method, the whole large variation range is further divided into several clusters composed of pixels varying in small range of \( I_0 \). As shown in Fig. 2, each cluster is distinguished by a significant peak together with its surrounded two significant valleys and along the positive direction of \( I_0 \), the clusters are marked from 1 to \( m \), which is the total number of determined clusters. Since the pixels within a certain cluster have similar reflectivity, a single exposure would be sufficient for a single cluster. To predict an exposure time that is able to entirely cover each cluster, we choose the value of \( I_0 \) corresponding to the significant valley on the right side of each cluster to calculate the exposure time. For example, in Fig. 2, \( I_0_{c1} \) is used to compute optimal exposure time for cluster 1, \( I_0_{c2} \) for cluster 2 and so on.

To calculate optimal exposure time for each cluster, Eq. (13) has been changed into

\[
t_{\text{opt}} = \frac{I_{\text{ideal}}}{I_0}
\]

(14)

where \( I_0 \) is the horizontal axis coordinate of the significant valley on the right side of cluster \( i \) \((i = 1, 2, \ldots, m)\), and \( t_{\text{opt}} \) is the calculated optimal exposure time for cluster \( i \).
can be generated by
\[ I_{\text{tech}}(x,y) = \sum_{i=1}^{m} I_i^{\text{opt}}(x,y) \times M_i(x,y) \]  
(16)

where \( I_i^{\text{opt}} \) is the captured image at exposure time \( t_i^{\text{opt}} \). Eq. (16) shows that in raw image \( I_i^{\text{opt}} \), pixels within cluster \( i \) which has been optimally exposed at \( t_i^{\text{opt}} \) are preserved for creating a new synthetic image. It should be noted that the \( I_{\text{tech1}} \) is a fused image for one phase-shift image; thus, \( N \) frames of composite phase-shift image need to be formed when the N-step phase shifting algorithm is adopted to calculate phase.

2.3. Technique II: polarization-based high dynamic range measurement technique

In the previous section, Technique I is proposed to handle the diffuse surface with LRR. However, there are still lots of objects with specular surface that need to be measured. The difficulty of inspecting this kind of objects lies in the fact that the camera sensor would be saturated when the reflected intensity from the shiny area exceeds the maximum intensity quantization level of the camera. This will result in no fringes modulated by the highlight surface being correctly captured by the camera. Theoretically, the technique based on multi-exposure can be applied in such scenario; however, it generally requires a large number of exposure time to cover the whole measured surface due to the great dynamic range of the specular region, making the whole measurement process rather cumbersome and time-consuming. Thus, to eliminate the effect of specular highlight, polarization method is introduced and Fig. 3 demonstrates its schematic diagram. Two polarized filters are placed in front of the projector and camera respectively. The projected incident light turns into linear polarized light after it passes through the first polarizer and after the reflection occurs on measured object, the original linear polarized light has changed into a compound one composed of diffuse lobe, specular lobe and specular spike. In the specular parts, the reflected component maintains its state of linear polarization while in the diffuse component, the original linear polarized light transforms into the light vibrating in all directions. Finally the compound light passes through the second polarizer before it is captured by the camera. According to the whole process, the final captured image can be written as the sum of
diffuse component $l_d$ and specular component $l_s$

$$l = l_d + l_s = \frac{1}{2}l_{in}\alpha d + \frac{1}{2}l_{in}\alpha r_s \cos^2 \theta$$  (17)

where $l_{in}$ is the projected incident light, $\alpha$ the surface reflectivity and $\theta$ the angle between the transmission axes of the two polarizers. The parameter $r_s$ is used to indicate the proportion of diffuse component in the reflected compound light and $r_d$ shows the ratio of the specular component. Since the compound light is only composed of these two parts, $r_d$ and $r_s$ are supposed to satisfy the relation $r_d + r_s = 1$ and based on the relation, we classify specular reflection into two types. For the one with $r_s$ nearly equal to 1, we define it as a strong specular reflection (SSR), otherwise the reflection will be treated as a weak specular reflection (WSR).

For this Technique II, we only focus on the WSR, in which the specular component accounts for less proportion than the diffuse component does. From Eq. (17), we can readily deduce that the specular component can be entirely removed when the angle $\theta$ becomes 90°. Thus using this strategy the intense highlight can be eliminated. However, this approach is not very reliable because the received intensity of the whole image will be attenuated due to the presence of the two polarizers, and this would lead to low signal-to-noise ratio of the captured fringes. In order to solve this problem, the proposed Technique I is introduced into the Technique II to compensate the intensity reduction since the Technique I is able to predict optimal exposure time on the basis of captured image $I_{opt}$. Although $I_{opt}$ weakens because of the polarizers, the $I_{opt}$ will not change and it will constantly be 254. So the prediction for optimal exposure time will not be affected by the introduced polarizers. Besides, as the specular highlight is removed, the rest reflected light is merely composed of diffuse light. Therefore technique is also competent to measure the scene simultaneously involving surfaces with WSR and LRR.

2.4. Technique III: complex specular reflection high dynamic range measurement technique

This technique is presented to measure object with SSR, in which the ratio of specular component is considerably larger than that of the diffuse component, namely the $r_s$ will be close to 1. Thus, according to Eq. (17), we will have

$$l = l_s = \frac{1}{2}l_{in}\alpha r_s \cos^2 \theta$$  (18)

Eq. (18) indicates that the captured light intensity is determined completely by the angle $\theta$ when SSR occurs. It is obvious that if $\theta$ equals to 90° just as the case of Technique II, the recorded intensity $l$ would be close to zero, which means that the camera could hardly detect any fringes. This is the reason for the development of Technique III. To capture fringes on this kind of surface, $\theta$ should not be set as 90°. Meanwhile, it is also inappropriate for the angle $\theta$ to be far less or more than 90°. This is because the captured intensity $l$ would be too intense, which may result in camera sensor saturation. So, in Technique III, we adjust the $\theta$ to 90° first and then slightly rotate one of the polarizers to change the angle. As $\theta$ is away from 90°, the captured fringes would emerge more and more clearly till the pixels become saturated. So, the angle is determined when the surface with SSR shows the clearest fringes. As the projected fringes can be recorded robustly after the angle alteration, the followed reconstruction can be achieved readily.

So far, the Technique III can merely cope with the simple scene only composed of surface with SSR. To make this technique be capable of measuring more complex scene and be more applicable, we have further developed it. To inspect scene simultaneously involving surfaces with LRR, WSR and SSR, Technique II is introduced into Technique III first. According to the previous section, by Technique II, except that fringes on surface with SSR will be captured with poor quality, high contrast fringes on surfaces with LRR and WSR can be obtained. Then, the strategy of angle alteration follows to capture distinct fringes on surface with SSR. Finally, synthesized fringe image is generated by fusing the composite fringe image from Technique II and the fringe pattern is captured after angle alteration. For picking out the pixels related to SSR, we introduce the concept of degree of polarization:

$$d = \frac{l_{max} - l_{min}}{l_{max} + l_{min}}$$  (19)

where $l_{max}$ is the captured image when the transmission axes of the polarizers are parallel and $l_{min}$ is the acquired image when they become perpendicular. Based on Eq. (17), $l_{max}$ and $l_{min}$ can be written as

$$l_{max} = \frac{1}{2}l_{in}\alpha r_s + \frac{1}{2}l_{in}\alpha r_d$$  (20)

$$l_{min} = \frac{1}{2}l_{in}\alpha r_d$$  (21)

Then substituting these two equations into Eq. (19), we have

$$d = \frac{l_{max} - l_{min}}{l_{max} + l_{min}} = \frac{2l_{in}\alpha r_s}{l_{max} + l_{min}}$$  (22)

Eq. (22) shows that the degree of polarization entirely depends on $r_s$. As SSR has much larger $r_s$ than other reflections do, the degree of polarization can be used to differentiate the surface with SSR from surfaces with other reflections. Thus, we set a threshold $d_{th}$ to $d$ and the criterion follows

$$d(x, y) \geq d_{th}$$  (23)

The measured surface satisfying Eq. (23) are regarded as the one with SSR.

For the fusion of raw composite image formed by the Technique II and the image acquired after angle alteration, two masks $M_{tech2}$ and $M_{alter}$ are created as

$$M_{tech2}(x, y) = \begin{cases} 
0, & \text{if } d(x, y) \geq d_{th}(x, y) \\
1, & \text{otherwise}
\end{cases}$$

$$M_{alter}(x, y) = \begin{cases} 
1, & \text{if } d(x, y) \geq d_{th}(x, y) \\
0, & \text{otherwise}
\end{cases}$$  (24)

According to Eq. (24), only the pixels corresponding to SSR will be valid in mask image $M_{alter}$ while they will be invalid in mask image $M_{tech2}$. Finally, a new synthetic fringe image can be generated by

$$I_{tech3}(x, y) = I_{tech2}(x, y) \times M_{tech2}(x, y) + I_{alter}(x, y) \times M_{alter}(x, y)$$  (25)

where $I_{tech3}$ is the composite fringe image solved from the Technique II and $I_{alter}$ is the fringe image captured after the angle adjustment. Eq. (25) shows that high quality fringes on surfaces with LRR, WSR and SSR are all well preserved in the newly fused image.

3. Experiments

We developed a 3-D shape measurement system based on the fringe projection technique. It includes an industrial CCD camera GE680 (Allied Vision Technologies) with the resolution of 640 × 480, a DLP Light Crafter DMD kit with a resolution of 608 × 684 and a data processing device the Dell OptiPlex 990. The used polarizers have a diameter of 50 mm, clear aperture of 45 mm with extinction ratio of 100 : 1. To eliminate the impact of ambient
light, the experiments were conducted at night with all fluorescent lights off. The four-step phase shifting algorithm and temporal phase unwrapping method were adopted to realize the phase retrieval, and the unwrapped phase was converted to 3-D coordinate after the system calibration [16]. To ensure the accuracy of the measurement, we tested the gray-scale response of the used projector first, and the result is shown in Fig. 4 from which the projector shows a good linearity for 8-bit intensity level projection. Then, we measured the linearity of the captured intensity and exposure time for the camera sensor. The experimental result indicates that the adopted CCD camera behaves linearly under both conditions with and without the polarizers.

3.1. High dynamic range measurement for diffuse objects with LRR

In this experiment, the measured scenario was composed of a white plaster model (in the left) and two paper boxes of uniform light brown (in the lower right) and uniform dark blue (in the upper right) respectively. Firstly, we conducted the measurement by a traditional method in which only a single exposure was applied. The single exposure time was set to be $t_{\text{single}} = 17,000 \mu s$, and Fig. 5 illustrates the measurement results of the traditional method. Fig. 5(a) shows one of the captured high frequency fringe images and Fig. 5(b) one of the low frequency fringes. The corresponding 3-D model is shown in Fig. 5(c).

Then the proposed Technique I was implemented. The projector firstly projected uniform bright light (255, 255, 255) and exposure time $t_0$ was set as $17,000 \mu s$ to capture the image $I_0$ that is shown in Fig. 6(a). Then the histogram of $I_0$ was calculated

![Fig. 4. The gray-scale response curve of the projector.](image)

![Fig. 5. Measurement results of traditional method of single exposure. (a) Representative fringe image of high frequency; (b) representative fringe image of low frequency; and (c) 3-D reconstruction models.](image)

![Fig. 6. Captured image $I_0$ and the corresponding histogram. (a) Image $I_0$; and (b) computed histogram of $I_0$.](image)
as illustrated in Fig. 6(b) in which three clusters can be roughly observed. So three exposure times would be adequate to meet the requirement of measuring the scene. On the right side of these clusters, the significant valleys ($I_{01} - I_{03}$) were used to calculate the needed optimal exposure time for each cluster. By Eq. (14), the corresponding exposure time were computed as $t_{1 opt} = 93.869 \, \mu s$, $t_{2 opt} = 38.553 \, \mu s$ and $t_{3 opt} = 17.000 \, \mu s$. Fig. 7 shows the fusion process of the captured raw fringe images for generating a composite one. The image $I_{i opt}$ ($i = 1, 2, 3$) represents the captured phase-shifting image at the predicted exposure time $t_{i opt}$ and $I_{i opt} \sim I_{i opt}$ corresponded to the same phase shift fringe. $M_i$ is the created mask according to Eq. (15). In the procedure of the combination, the raw fringe images multiplied their corresponding masks first to select the regions being optimally exposed at each exposure time. Then the masked images added up together to generate a new fused fringe image. Fig. 8(a) shows another fringe image of low frequency formed by the same way. After all the needed fringe images were generated, the absolute phase map

![Fringe image fusion process of the Technique I.](image)

Fig. 7. Fringe image fusion process of the Technique I.

![Resultant images of the Technique I.](image)

Fig. 8. Resultant images of the Technique I. (a) A formed low frequency fringe image by the Technique I; (b) calculated absolute phase map; and (c) 3-D results in different views.
Fig. 9. Comparison of the tradition method and the Technique I. (a) Shows the schematic of traditional single exposure method; and (b) shows the schematic of the proposed Technique I. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Fig. 10. Comparison between the plots of the measured surfaces from the two methods. (a) Plot of surface of the white plaster model from traditional method; (b) plot of surface of the white plaster model from the Technique I; (c) plot of surface of the light brown box from traditional method; (d) plot of surface of the light brown box from the Technique I; (e) plot of surface of the dark blue box from traditional method; and (f) plot of surface of the dark blue box from the Technique I. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
was calculated and shown in Fig. 8(b) and the corresponding 3-D model is illustrated in Fig. 8(c). As the difference between the traditional method and the Technique I is not obvious by visual observation of the 3-D results, quantitative comparisons were made.

Fig. 11. Effect of WSR and experimental images of the traditional method. (a) Measured scene without highlight elimination; (b) the scene after introducing the two perpendicular polarizers (image $I_0$); (c) representative fringe image of high frequency; and (d) representative fringe image of low frequency.

Fig. 12. Experimental images of the Technique II. (a) Calculated histogram of $I_0$; (b) one of the generated high frequency fringe images by the Technique II; (c) one of the generated low frequency fringe images by the Technique II; and (d) shows the selected rows on the surfaces for plots.

Fig. 9(a) shows the schematic of the traditional technique, where the dark red was used to suggest that the whole scenario was inspected at the single exposure time $t_{single}$ and Fig. 9 (b) shows the schematic of the Technique I, in which three colors were adopted to indicate that the involved objects were measured.
at three different exposure times. For comparison, on each object, we plotted one row of their surface, as shown by the dotted lines. The results are illustrated in Fig. 10. Fig. 10(a) and (b) shows the cross-sections of the reconstruction of the white plaster model from the traditional method and the Technique I respectively. In Fig. 10(a), the selected surface was measured at single exposure time \(t_{\text{single}}\) and some parts of the curve are slightly prickly, while, as shown in Fig. 10(b), two exposure times were used by the Technique I and the whole curve shows good smoothness. In particular, the former rough parts became smooth when exposure time \(t_{\text{opt}}\) was adopted. By the way, although the plotted row of the plaster model was measured at two exposure times which lead to the captured fringes with different signal-to-noise ratios, this did not affect the accuracy of Technique I as can been seen in Fig. 10(b). The reason is that we have removed the ambient illumination and provided sufficient exposure for each region.

Fig. 10(c) and (d) shows the plots of the row of the light brown box from the two approaches. In Fig. 10(c), using the traditional way, the exposure time was unchanged and noise can be clearly observed. By contrast, when the Technique I was applied, the surface was retrieved precisely as shown in Fig. 10(d). After that, Fig. 10(e) and (f) illustrates the measured cross-sections of the dark blue box. As shown in Fig. 10(e), by the tradition method, the exposure time was not altered and the curve was very spinous. Specially, for the pixels within the ranges of \([0, 100]\) and \([200, 300]\), the corresponding results are of significant errors. In Fig. 10(f), by implementing the Technique I, the entire curve is straight, which implies that the surface was measured precisely when the exposure time \(t_{\text{opt}}\) was used.

Since the exposure time was fixed in the traditional method of single exposure, it is very difficult for it to measure bright and dark surfaces simultaneously. In contrast, the proposed Technique I is capable of predicting the needed exposure time for different surface and measuring them accurately at the same time.

3.2. HDR measurement for the scene containing object with WSR

This experiment was conducted to validate the proposed Technique II. The tested scene was composed of a white ceramic bowl, a painted green bottle (in the upper right) and a dark blue paper box (on the left). We firstly projected uniform white light (255, 255, 255) onto the objects. Fig. 11(a) shows a captured image when no polarizer was introduced. Specular highlight can be clearly observed on the front surfaces of the painted bottle and the ceramic bowl. After placing two plorizers in front of the camera and the projector separately, and adjusting the angle \(\theta\) between their transmission axes to be 90°, another image was acquired and demonstrated in Fig. 11(b), where the highlights were completely removed. For comparison, the measurement was firstly conducted by the traditional method. Two representative images of high and low frequency fringe were captured and shown in Fig. 11(c) and (d). The corresponding 3-D reconstruction result is depicted in Fig. 13(a). It can be found that although the contour of the scene was reconstructed generally, some involved objects were still of server noises like the dark blue box in the left. Due to the low reflectivity of its surface and the reduction of the projected intensity caused by the polarizers, the corresponding reconstruction was very rough.

Then the developed Technique II was used to measure the scene. We adopted Fig. 11(b) as the \(I_0\) and recorded the corresponding exposure time \(t_0 = 12,000 \, \mu s\). Fig. 12(a) shows the histogram of \(I_0\) from which four clusters can be observed. Thus four corresponding significant valleys \((I_01 - I_04)\) were used to calculate optimal exposure times for the four clusters. From Eq. (14), the related exposure times were acquired as \(t_{\text{opt}}^1 = 152,400 \, \mu s, t_{\text{opt}}^2 = 38,582 \, \mu s,\)
3.3. HDR measurements for scenario comprising object with SSR

To validate the presented Technique III, a simple scene only containing object with SSR was tested first and then measurement of a more complex scene with objects with SSR, WSR and LRR followed. As the aluminum alloy always shows the property of SSR, in the simple scenario, a tool whose bottom is made of that material was inspected. Fig. 15(a) shows an acquired image of the tool, in which the specular reflection is very intense and nearly covers the entire surface of the aluminum alloy. For comparison, the Technique II was utilized to measure the scene first. Uniform bright light was projected onto the scene and two polarizers were

\[ t_{\text{opt}}^1 = 20.594 \, \mu s \quad \text{and} \quad t_{\text{opt}}^4 = 12.000 \, \mu s \]

Then raw fringe images were captured at these exposure times, and using Eqs. (15) and (16) the image fusion process was achieved. Fig. 12(b) and (c) shows two selected newly generated phase-shift images in which fringes of high contrast for all objects were acquired and this resulted in all the properly retrieved surfaces showed by Fig. 13(b).

To compare the Technique II and the traditional method quantitatively, on each surface we plotted a row to investigate the measurement accuracy, as shown in Fig. 12(d). The experimental results are illustrated in Fig. 14. Fig. 14(a) and (b) shows the plots for the surface of the ceramic bowl. It can be seen that this surface was accurately measured by both methods. Fig. 14(c) and (d) demonstrates the cross-sections of the reconstruction of the green bottle using the tradition way and Technique II respectively. It can be observed that the plotted curve was little unsmooth despite the shape of the bottle can be obtained by the conventional method. By contrast, when the Technique II was carried out, the curve was smooth without any pricks. Then, Fig. 14(e) and (f) shows the plots for the surface of the dark blue box. In Fig. 14(e), by the traditional approach, the acquired curve was rather spinous and it seemed that the measured height was obscured completely by the measurement errors. While, in Fig. 14(f), good smoothness was shown throughout the entire curve, which means the surface was measured precisely by the Technique II.

From the results, the developed Technique II can measure more accurately and precisely than the traditional method. This is because the proposed method is immune to the reduced intensity attributed to the polarizers and capable of predicting optimal exposure time to capture high contrast fringes.
Fig. 15. Experimental images of the test of simple scene with SSR. (a) Measured tool with surface of aluminum alloy; (b) Image $I_0$; (c) obtained histogram of $I_0$; (d) fused high frequency image by the Technique II; (e) fused low frequency image by the Technique II; (f) captured high frequency fringe image after angle adjustment; and (g) captured low frequency fringe image after angle adjustment.

Fig. 16. 3-D reconstructions by the two approaches. (a) Results from the Technique II; and (b) results from the Technique III.
Fig. 17. Experimental images of the complex scene by the Technique III. (a) Image shows the effect of WSR and SSR; (b) captured image \( I_0 \); and (c) obtained histogram of \( I_0 \).

Fig. 18. Fringe image fusion process of the Technique III.
placed separately in front of the camera and the projector. To remove the specular highlight, the angle $\theta$ was adjusted as $90^\circ - 1^\circ$. Then image $I_0$ was captured at exposure time $t_0 = 24,000 \mu s$, as shown in Fig. 15(b). Fig. 15(c) shows the calculated histogram of $I_0$, in which two clusters can be seen. By using Eq. (14), two exposure times were obtained as $t_{1\text{opt}} = 225,777 \mu s$ and $t_{2\text{opt}} = 76,200 \mu s$. After capturing raw fringe images at these two exposure times and creating corresponding masks, the fusion process was then carried out. Fig. 15(d) and (e) shows two representative generated composite fringe images, in which the contrast of fringe on the surface of the aluminum alloy was very low and this resulted in incorrect 3-D reconstruction as shown in Fig. 16(a). To obtain the clear fringes, an angle alteration of $4^\circ$ was made to the $\theta$ to let it be slightly away from $90^\circ$. After the angle adjustment, fringes of higher contrast were acquired, as shown in Fig. 15(f) and (g). The final 3-D reconstruction was illustrated in Fig. 16(b) where the surface of the aluminum alloy was measured correctly.

After the measurement of the simple scene, a more complex scenario composed of a white shiny plastic cup, a dark blue box (in the upper right), a white plaster model and the tool (in the lower left) was inspected. Fig. 17(a) shows the tested scene where WSR has arisen on partial surface of the plastic cup and SSR nearly the whole surface of the aluminum alloy. To implement the Technique III, Technique II was firstly carried out. After placing the two perpendicular polarizers and projecting uniform bright light, image $I_0$ was captured at $t_0 = 5000 \mu s$, as shown in Fig. 17(b). Then the histogram of $I_0$ was calculated and shown in Fig. 17(c) where three clusters can be determined. From Eq. (14), the corresponding exposure times were obtained as $t_{1\text{opt}} = 39,687 \mu s$, $t_{2\text{opt}} = 16,282 \mu s$ and $t_{3\text{opt}} = 7987 \mu s$. Fig. 18 shows the whole process of image fusion in the Technique III. The $I_{i\text{opt}}(i=1,2,3)$ represents the captured fringe image at the predicted exposure time $t_{i\text{opt}}$ and the corresponding mask $M_i$ was developed using Eq. (15). $I_{\text{Tech2}}$ shows a representative formed raw composite fringe image by the Technique II. Since the fringes on the surface of the aluminum alloy are of low contrast in $I_{\text{Tech2}}$, we rotated one of the polarizers by $4^\circ$ and captured a new fringe image $I_{\text{alter}}$ as shown in Fig. 19(a) in which the surface of aluminum alloy showed clearer fringe pattern. Then, to obtain the map of degree of polarization, the projector projects uniform light (255, 255, 255) again and the
two polarizers were adjusted to be parallel to photograph the image $I_{\text{max}}$. After that they were set to be orthogonal for capturing image $I_{\text{min}}$. These two images are shown in Fig. 19(b) and (c). The map of degree of polarization was then computed by Eq. (19), as shown in Fig. 19(d), in which the surface of the aluminum alloy is much brighter than the rest surfaces. So to identify this strong specular surface, the threshold $d_{\text{th}}$ was set as 0.85 and then two masks ($M_{\text{Tech2}}$ and $M_{\text{Alter}}$) were developed according to Eq. 24 for the image fusion. As Fig. 18 has shown, the raw composite image $I_{\text{Tech2}}$ multiplied the mask $M_{\text{Tech2}}$, generating an image where all the surfaces were retained except the one with SSR, and image $I_{\text{Alter}}$ multiplied the mask $M_{\text{Alter}}$, creating a masked image in which only the region of SSR was preserved. Finally, the two masked images added up together for forming a new fused image $I_{\text{Tech3}}$ in which all the surfaces with different reflectivity properties showed high quality fringe patterns. Fig. 20 shows the 3-D reconstruction model by using the Technique III. From the result, surfaces with SSR, WSR and LRR were successfully measured at the same time.

3.4. Precision test for the High dynamic range 3-D shape measurement solution

Since the Technique I is the core technique among the three techniques, its precision is tested to represent for the whole solution. To perform the evaluation, we measured a planar black/white calibration board. Fig. 21(a) shows the image of the used calibration board. For comparison, the traditional technique of single exposure was implemented first. The exposure time $t_{\text{single}}$ was set as 25,000 μs, one the captured fringe image is shown in Fig. 21(b) and the 3-D reconstruction result is shown in Fig. 22(a), in which lots of errors can be seen.

Then, the Technique I was applied to measure the scene. Fig. 21(a) is used as the image $I_0$ which was acquired at exposure time $t_0 = 30,000$ μs. The calculated histogram of $I_0$ is illustrated in Fig. 21(c), where two clusters were contained in the intensity distribution that means two exposure times would be sufficient to be applied for this scene. After capturing the raw fringe images at the calculated exposure times, image fusion was conducted. One of
the composite fringe images is shown in Fig. 21(d) and Fig. 22(b) shows the 3-D reconstruction model. To quantitatively assess the measured results, cross-section plots of 240th row of the retrieved planes obtained by the traditional method and Technique I are illustrated in Fig. 22(c) and (e) respectively. The distances between the measured results and the fitted curves were calculated to evaluate the precision. The measurement error of the traditional way is shown in Fig. 22(d) with standard deviation of 0.5257 mm, and that of the Technique I is figured in Fig. 22(f) with standard deviation of 0.0453 mm. The experimental results indicate that the precision can be improved by an order of magnitude by the proposed solution.

Since the solution is developed to be universally applicable, which means it can also be used to measure other scenarios, to facilitate the appliance of the solution, we have listed several common measurement scenes and their applicative measuring techniques in Table 1. For simplification, surface with LRR denoted as Surface A, surface with WSR as Surface B and surface with SSR as Surface C.

4. Conclusion

We have presented a general solution for high dynamic range 3-D shape measurement. It is composed of three newly developed techniques. The Technique I predicts appropriate exposure times based on the deduced statistics distribution of the reflectivity, and generate new fringe image by selecting the pixels with best fringe quality from the raw fringes captured at the predicted exposure times. The Technique II is executed by the introduction of two perpendicular polarizers into our Technique I for measuring the occasions with WSR. For the scenes with SSR, Technique III firstly adopts the Technique II to generate raw composite fringe image. Then by the way of making a proper angle alteration to the perpendicular polarizers, an image with high contrast fringe pattern on strong specular surface is captured. With the help of method of the degree of polarization, a new composite fringe image is obtained by fusing the fringe image photographed after angle alteration and the raw synthetic fringe image generated from the Technique II. Our experiments have verified that the proposed general solution can effectively handle the scene with different reflective properties from simple to complex.

To apply the proposed solution, it should be noted that the measurement environment needs to be dark or the used projector can provide intense light projection. The reason is that the signal-to-noise ratio of the reflected fringe pattern may be lowered by the influence of the ambient illumination, which may result in poor measurement accuracy. Besides, the selection of predicted exposure time and the alteration of the angle between the transmission axes need to be made by human intervention. This means the solution is not appropriate to real-time reconstructions. Our future work will involve developing new technique that is insensitive to the effect of ambient light and can be implemented with less human intervention.

Acknowledgments

This project was supported by the Research and Innovation Plan for Graduate Students of Jiangsu Higher Education Institutions, China (No. CXLX13_177), the Research Fund for the Doctoral Program of Ministry of Education of China (No. 20123219110016), the National Natural Science Foundation of China (No. 61271332) and the Open Research Fund of Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense.

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