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Keywords
3D shape measurement, phase shifting, step height, multiple wavelength

Disciplines
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Digital Multiple Wavelength Phase Shifting Algorithm

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ABSTRACT
This paper presents a digital multiple-wavelength phase-shifting technique for three-dimensional shape measurement. The projected phase-shifted fringe images have wavelengths of \( \lambda_k = \frac{W}{2k} \) (k = 1, 2, 3...). The phase unwrapping is not needed for the longest wavelength because a single fringe covers the whole area. The shorter wavelength phase, \( \phi_k(x,y) \), is unwrapped by referring to the previously unwrapped longer wavelength phase, \( \Phi_{k-1}(x,y) \), pixel by pixel without accessing its neighborhood pixels. Experiments demonstrate that this technique has low noise and less sensitivity to motion. It can be used to measure arbitrary step height and multiple objects simultaneously.

Keywords: 3D shape measurement; phase shifting; step height; multiple wavelength.

1. INTRODUCTION
High-resolution, accurate 3D shape measurement is increasingly important in the last several decades, with applications in manufacturing, medical sciences, computer sciences, etc.

Traditionally, laser interferometries are widely used because of their accuracy and stability. A variety of phase-shifting algorithms have been proposed for high resolution and high accuracy measurement. One of the advantages of the phase-shifting algorithms is that they measure object point by point, and is less sensitive to surface reflectivity variations. For a single-wavelength phase-shifting algorithm, the phase computed directly from the phase-shifted fringe images ranges from \(-\pi\) to \(+\pi\). For high accuracy measurement, multiple fringe stripes are usually used, where a phase unwrapping algorithm is needed to obtain continuous phase map. Over the years, many phase unwrapping algorithms have been developed. Unfortunately, none of them can 100% successfully unwrap arbitrary phase map without pre-knowledge of the measured object, especially when the object surface profile has sharp changes.

For a single-wavelength phase-shifting algorithm, the phase difference between two adjacent pixels cannot be be larger than \( \pi\lambda/2 \) in optical path difference, or the step height cannot be larger than \( \lambda/4 \) on the object. Therefore, to measure step height objects, a two-wavelength (\( \lambda_1 \) and \( \lambda_2 \)) phase-shifting algorithm was used. For this method, the measurable step height increases by making the equivalent wavelength to be longer than any of the wavelength used. The equivalent wavelength can be written as

\[
\lambda_{eq} = \frac{\lambda_1\lambda_2}{|\lambda_1 - \lambda_2|}
\]

However, the two-wavelength phase-shifting algorithm measures increases the step height measurement capability by sacrificing its data quality. The signal to noise ratio (SNR) is smaller than that using only a single-wavelength phase-shifting algorithm for either \( \lambda_1 \) or \( \lambda_2 \). This is not desirable since the noise can hide the signal if the equivalent wavelength, \( \lambda_{eq} \), is too long. Therefore, \( \lambda_1 \) (assume \( \lambda_1 > \lambda_2 \)) is 3 or 4 times of \( \lambda_2 \) is recommended.

Multiple-wavelength phase-shifting algorithms have been developed to further increase equivalent wavelength by using more than two wavelengths. They can measure larger step height with lower noise than a two-wavelength phase-shifting algorithm. They were used widely to measure larger step height. Huntley et al proposed a technique called temporal phase unwrapping algorithm and apply it to measure discontinuous objects. The fundamental concept of this technique is that the phase is unwrapped in time axis rather than in \( x - y \) plane spatially. Therefore, the measurement is performed point by point. However, traditionally, the fringe images were generated by laser interferences, and it is difficult to generate the desired wavelength precisely.

Zhao et al proposed a two-wavelength phase-shifting algorithm using a fringe projection technique. In this approach, two sets of fringe images with different wavelength were projected using a slide project and captured by a camera. A
similar phase correction algorithm as the one used in our paper (will be discussed in detail in Subsec. 2.3) was used by referring to the longer wavelength phase point by point. However, because this technique utilized two wavelengths for the measurement, similar to other two-wavelength algorithms, the noise plays a major role for the final measurement. Although the authors addressed an error function to minimize the error caused by the noise, if the wavelength difference is significantly, it might prevent correctly unwrapping the phase for the shorter wavelength. Moreover, using slide projector may have problem of precisely controlling the required wavelength and/or phase shift.

Saldner and Huntley developed a measurement system that used temporal phase unwrapping algorithm and spatial light modulator-based fringe projector. For this system, a digital projector was used, and the phase shift as well as the wavelength can be produced precisely. However, since only the first and the last spatial frequency phase maps were used, and it was shown by Huntley and Saldner that the noise plays a more significant role for this technique than the technique proposed by Zhao et al. Recently, Towers proposed an optimum frequency selection for the multiple wavelength methods. Later they verified, by simulation, an optimum three-frequency algorithm for 3D shape measurement.

With the rapid development of the digital display technology, digital phase-shifting techniques are increasingly adopted. A digital fringe projection and phase-shifting algorithm is able to control the phase shift and the wavelength accurately because of its digital fringe generation nature. The system using this technique is also commonly called structured light system. For such a system, a digital video projector is used to project computer generated phase-shifted fringe images. This technique has been proven to be a powerful method to perform measurement rapidly at good accuracy. We have developed a real-time absolute 3D shape measurement based on a fast three-step phase-shifting algorithm. However, similar to laser interferometries, the single-wavelength digital phase-shifting techniques suffer if the object surface has sharp changes. Therefore, to successfully measure the object, its surface must be smooth. This shortcoming limits its usage because the surface smoothness cannot always been guaranteed.

In this research, we propose a digital fringe projection and multiple-wavelength phase-shifting algorithm to extend its measurement range and increase its tolerance to the surface discontinuities. For this method, a series of fringe images with the wavelengths of \( \lambda_k = \frac{W}{kW} \) \( k = 1, 2, 3, \ldots \) are captured for 3D shape measurement. Here \( W \) is the number of pixels of the projector horizontally (if fringe stripes are vertical) or vertically (if the fringe stripes are horizontal). For the fringe images using wavelength of \( \lambda_1 \), a single fringe stripe covers the whole measurement area. Therefore, no phase unwrapping is required. The successively phase maps, \( \phi_k(x,y) \), are unwrapped using their previous unwrapped phase maps, \( \Phi_{k-1}(x,y) \), pixel by pixel without accessing their neighborhood pixels. Subsection 2.3 will introduces this multiple-wavelength phase-shifting algorithm in detail.

For this proposed method, because the measurement is done pixel by pixel, it can be used to measure arbitrary step height with high accuracy. It can also be used to simultaneously measure multiple separate objects. Moreover, since the longer wavelength phase is only used as reference to obtain the integer values that are used to correct the \( 2\pi \) discontinuities, its noise does not significantly affect the shorter wavelength phase. Therefore, high SNR can be obtained using this technique. Moreover, because only the shortest wavelength phase is used to compute the coordinates, this technique is not very sensitive to motion. We will show that this technique can measure a human face successfully.

Section 2 introduces the single-wavelength, two-wavelength, and multiple-wavelength phase-shifting algorithms. Section 3 addresses the background removal technique. Section 4 introduces the system setup. Section 5 shows some experimental results. Section 6 discusses the advantages and shortcomings of this proposed technique, and Section 7 summarizes the work.

### 2. PHASE-SHIFTING ALGORITHMS

#### 2.1 Single-wavelength phase-shifting algorithm

Phase-shifting algorithms are widely used due to their measurement speed and non-contact nature. For the single wavelength phase-shifting algorithm, a number of fringe images with certain phase shift are used to obtain the phase. The 3D coordinates are computed from the phase based on calibration. There are a number of phase-shifting algorithms have been proposed including three-step, four step, double-three step, and five step.
A three step phase-shifting algorithm with a phase shift of $2\pi/3$ can be written as,

\begin{align*}
I_1(x,y) &= I'(x,y) + I''(x,y)\cos[\Phi(x,y) - 2\pi/3], \\
I_2(x,y) &= I'(x,y) + I''(x,y)\cos[\Phi(x,y)], \\
I_3(x,y) &= I'(x,y) + I''(x,y)\cos[\Phi(x,y) + 2\pi/3].
\end{align*}

(1) \hspace{1cm} (2) \hspace{1cm} (3)

Where $I'(x,y)$ is the average intensity, $I''(x,y)$ the intensity modulation, and $\Phi(x,y)$ the actual phase to be solved for. From these three equations, we have

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

(4)

\[ \phi(x,y) \text{ ranging from } -\pi \text{ to } +\pi \text{ is called the wrapped phase with a modulo of } 2\pi. \] The actual phase is

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

(5)

Where $m(x,y)$ are integers. If only a single fringe stripe is used, $\phi(x,y) = \Phi(x,y)$ and $m(x,y) \equiv 0$, no phase unwrapping is needed. However, if multiple fringe stripes are used, $m(x,y)$ are not always 0s, a phase unwrapping algorithm is required to remove the $2\pi$ discontinuities by detecting the correct integers, $m(x,y)$, from neighborhood point phase.\(^2\) Though various phase unwrapping algorithms have been proposed, none of them can always correctly retrieve the true phase value especially when the surface has sharp step height. Assume the wavelength used is $\lambda$. To remove $2\pi$ ambiguities from the phase map, the phase difference between two adjacent pixels of the phase map must be less than $\pi \lambda/2$ in optical path difference, or $\lambda/4$ on object surface.\(^3\)

Moreover, from Eqs.(1)-(3), we can obtain

\[ \gamma(x,y) = \frac{I''(x,y)}{I'(x,y)} = \frac{\sqrt{3}(I_1 - I_3)^2 + (2I_2 - I_1 - I_3)^2}{I_1 + I_2 + I_3}. \]

(6)

Here $\gamma(x,y)$, ranging from 0 to 1, is data modulation, which indicates the data quality with 1 being the best. It is commonly used for noise reduction, background removal, and phase unwrapping.

### 2.2 Two-wavelength phase-shifting algorithm

For a two-wavelength phase-shifting algorithm, assume the two phase maps are $\phi_1(x,y)$ and $\phi_2(x,y)$, respectively. The equivalent phase $\phi_{eq}(x,y)$ can be written as,\(^24\)

\[ \phi_{eq}(x,y) = \phi_1(x,y) - \phi_2(x,y). \]

(7)

Assume two wavelengths are $\lambda_1$ and $\lambda_2$, respectively, the equivalent wavelength is

\[ \lambda_{eq} = \frac{\lambda_1 \lambda_2}{|\lambda_1 - \lambda_2|}. \]

(8)

The phase unwrapping algorithm is used (if needed) to unwrap the equivalent phase map, $\phi_{eq}(x,y)$, to obtain a continuous phase map $\Phi_{eq}(x,y)$. The surface depth $z(x,y)$ is proportional to $\lambda_{eq}$, i.e.,

\[ z(x,y) \propto \lambda_{eq} \Phi_{eq}(x,y). \]

(9)

Assume $\lambda_1 > \lambda_2$, it can be shown that

\[ \lambda_{eq} \geq \lambda_1 \Leftrightarrow \lambda_1 < 2\lambda_2. \]

This means that if $\lambda_1 > 2\lambda_2$, the equivalent wavelength is actually shorter than the longer wavelength, $\lambda_1$, and two-wavelength technique does not help solve the phase ambiguity problem. On the other hand, if $\lambda_1 < 2\lambda_2$, the phase noise will be increased due to the scaling factor of the equivalent wavelength. Therefore, the two-wavelength phase-shifting algorithm helps solve the phase ambiguity problem by sacrificing the data quality (lower SNR). Therefore, to have good quality data, $\lambda_1$ is 3 or 4 times of $\lambda_2$ is commonly recommended.\(^7\)
2.3 Multiple-wavelength phase-shifting algorithm

From Eq.(8), we can see that if \( \lambda_1 = 2\lambda_2 \), the equivalent wavelength will be the same as the \( \lambda_1 \), therefore, the resultant phase noise will not be scaled up. Assume the projector has a resolution of \( W \times H \) and the projected fringe images are vertical. If we choose \( \lambda_1 = W \), the unwrapping step is not required because the single fringe covers the whole measurement area. That is,

\[
\Phi_1(x,y) = \phi_1(x,y). \tag{10}
\]

Here \( \Phi_1(x,y) \) represents the unwrapped phase, and \( \phi_1(x,y) \) the wrapped phase.

For the phase \( \phi_2(x,y) \), there will be two fringes in the measurement area. Hence,

\[
\Phi_2(x,y) = 2\pi m_2(x,y) + \phi_2(x,y). \tag{11}
\]

Here \( m_2(x,y) \) are integers.

Since \( \lambda_1 = 2\lambda_2 \), we have

\[
\Phi_2 = 2\Phi_1. \tag{12}
\]

That is

\[
m_2(x,y) = \frac{\Phi_1(x,y)}{\pi} - \frac{\phi_2(x,y)}{2\pi}. \tag{13}
\]

In the digital world, Eq.(13) becomes

\[
m_2(x,y) = \text{Round} \left[ \frac{\Phi_1(x,y)}{\pi} - \frac{\phi_2(x,y)}{2\pi} \right]. \tag{14}
\]

Here operator \( \text{Round}[] \) is to obtain the closest integer value. Therefore, the wrapped phase, \( \phi_2(x,y) \), can be unwrapped pixel by pixel by referring to the unwrapped longer wavelength phase \( \Phi_1(x,y) \). The advantage of this algorithm is that the phase \( \Phi_1(x,y) \) is only used to obtain integers \( m_k(x,y) \). Therefore, the noise of \( \Phi_1(x,y) \) does not significantly affect the noise of \( \Phi_2(x,y) \). Moreover, since the noise level of \( \phi_1(x,y) \) is approximately double that of \( \phi_2(x,y) \), obtaining correct \( m_k(x,y) \) can be guaranteed if the phase noise is not too large. On the other hand, if the phase maps have significant noise, they (except the one for the shortest wavelength) can be smoothed by a random noise reduction filter (e.g. Gaussian filter) to increase the robustness of the calculations. The phase map shortest wavelength is not smoothed to keep the original data untouched.

Once \( \Phi_2(x,y) \) is obtained, we can use it to correct \( \Phi_3(x,y) \), where \( \lambda_3 = \lambda_2/2 \), using a similar equation as Eq. (14). In general, for \( \lambda_k = \lambda_{k-1}/2 \),

\[
m_k(x,y) = \text{Round} \left[ \frac{\Phi_{k-1}(x,y)}{\pi} - \frac{\phi_k(x,y)}{2\pi} \right], \tag{15}
\]

and

\[
\Phi_k(x,y) = 2\pi m_k(x,y) + \phi_k(x,y). \tag{16}
\]

Equation (15) shows that the unwrapped phase is obtained pixel by pixel without accessing its neighborhood pixels in the same phase map, and the noise of the longer wavelength will not significantly affect that of the shorter ones. Therefore, this technique can measure surface profile with arbitrary step height, and the measurement noise is close to that using a single-wavelength phase-shifting technique with the shortest wavelength.

3. BACKGROUND REMOVAL

The background has to be removed to obtain high-quality data. Obviously, data modulation \( \gamma(x,y) \) in Eq.(6) and the average intensity value \( I'(x,y) \) can be used for this purpose. Thresholds are chosen to determine whether the data point is background or foreground. However, due to the camera and/or projector noise, our experiments demonstrated that using \( \gamma(x,y) \) and \( I'(x,y) \) is not sufficient to cleanly remove the background.

In this research, besides using intensity value and \( \gamma \) value, we use an additional criteria to remove the background. Assume the fringe stripes are vertical, the unwrapped phase is monotonically increasing (or decreasing) across the image horizontally. This constraint can also be used to remove the background. That is, assume the phase is increasing horizontally, the point is regard as a bad points if

\[
\Phi(x+1,y) - \Phi(x,y) < c_0. \tag{17}
\]

Here \( c_0 \) is the threshold to be determined by experiment (for our case, we used \( \pi/2 \)).
4. SYSTEM SETUP

The structured light system contains a digital light processing (DLP) projector and a charge-coupled device (CCD). The DLP projector used is PLUS U5-632h with a resolution of $1024 \times 768$. The focal range of the projector is $f = 18.4$ to $22.1$ mm. The digital micro-mirror device (DMD) chip used for this projector is 0.7 in.. The CCD camera is a digital CCD camera (Pulinx TM6740-CL) with an image resolution of $640 \times 480$. The camera sensor size is $7.4 \mu m$ (H) $\times$ $7.4 \mu m$ (V).

It uses a Fujinon HF16HA-1B lens with a focal length of 16 mm at f/1.4 to f/16. The exposure time used for the camera is approximately 8.33 ms. The frame grabber used in this system is a Matrox Solios XCL with CameraLink interface.

Figure 1 shows a photograph of the developed system.

5. EXPERIMENT

To verify the performance of the proposed technique, we implemented this proposed algorithm into our system and did some experiments. As shown in Figure 1, the projector is mounted vertically with 768 pixels horizontally, and the projected fringe images contain vertical stripes. The wavelengths used for the measurement are

$$\lambda_k = \frac{768}{2^k - 1}, k = 1, 2, ..., 6.$$  

Only six wavelengths are used for our experiments. For each measurement, three fringe images with a phase-shift of $2\pi/3$ for each wavelength and a total number of 18 fringe images are captured. The phases are computed using Eq.(4) for each wavelength, and then unwrapped successively using Eqs.(10)-(16).

In this research, the structured light system was calibrated using the approach addressed in Ref.(25). The absolute phase to coordinates conversion algorithm used the method introduced in our previous paper.23

We first measured a flat object, the phase maps for different wavelengths are shown in Fig. 2. It can be seen that for wavelength $\lambda_1 = 768$, the phase is continuous. The measurement results for different number of wavelengths are shown in Fig. 3. This experiment shows that the more number of wavelengths use, the lower the noise will be. This experiment also demonstrates that the noise of the longer wavelength phase does not drastically affect the noise of the shorter wavelength phase.

As a comparison, we only use the single wavelength phase $\phi_6(x,y)$ ($\lambda_6 = 24$) to perform the measurement using our previously developed phase unwrapping algorithm.26 Figure 4 shows the measurement result comparing with that obtained from the multiple-wavelength algorithm. It can be seen that the data noise level generated by the multiple-wavelength algorithm is similar to that generated by the single-wavelength phase-shifting technique with the shortest wavelength. This is one of the advantages of the multiple-wavelength algorithm over a two-wavelength algorithm that increases the measurement noise significantly.

Because this algorithm obtain the phase pixel by pixel without accessing its neighborhood pixels. It can be used to measure object with significant step height. Figure 5 shows the measurement result of an object with large step height. Figure 5(a) shows the photograph of the object. Figures 5(b)-5(d) show the shortest wavelength fringe images. As shown
Fig. 2. Wrapped phase for a flat board. (a)-(f) show the wavelengths of $\lambda_k = 768, 384, 192, 96, 48, \text{and } 24$, respectively.

in the white box of Fig. 5(d), the fringe becomes abnormal (sharp changes) as the height of object increase drastically. The step height cannot be measured correctly if only uses this single-wavelength phase-shifted fringe images are used. On the contrast, using the multiple-wavelength phase-shifting algorithm, the step height can be measured successfully. Figure 5(e) shows the measurement result rendered in 3D. The step height is separate from the base drastically. Figure 5(f) shows its cross section. This experiments demonstrated that even the object has a step height over 150 mm, this approach can still successfully perform the measurement.

Moreover, because the measurement is performed point by point, this technique can also be used to measure multiple separate objects or islands. To verify this, we measured two separate objects, two sculptures. Figure 6 shows the measurement results. Figure 6(a) shows the photograph of these objects. Figure 6(b) shows the 3D result rendered in shaded mode. Figure 6(c) shows the 3D result rendered with texture mapping, and Figure 6(d) shows the 3D result rendered in shaded mode viewing from another viewing angle. This experiment shows that even if two objects are completely separate, both of them were measured successfully using the proposed algorithm.

In addition, since only the final three fringe images are used to compute the coordinates, other fringe images are used only as references. Therefore, this technique can be used to measure an object with some motion. In this research, we measured a human face. During the measurement, the object was asked to sit in front of the system naturally. It is very difficult to make the subject motionless, therefore, we use this subject to test the system capability. The first row of Fig. 7 shows the measurement result using the proposed algorithm. The second row of this figure shows the 3D reconstruction result using the shortest wavelength ($\lambda_6 = 24$) phase map. It is obvious that because the face region is smooth, both approaches can obtain the geometry correctly. However, the traditional phase unwrapping algorithm cannot correctly position the neck region well because of the sharp changes from the face to the neck. On the contrast, the multiple-wavelength algorithm successfully reconstruct both the neck and face regions. The surface measurement errors for both algorithms look similar as expected. It should be noted that the 3D face data are all smoothed by a $5 \times 5$ Gaussian filter to remove the most significant random noise. This experiment demonstrated that this algorithm is less sensitive to motion, and can be used for slow motion measurement.
The advantages of the proposed multiple-wavelength phase-shifting algorithm include

- **Low noise.** As indicated in Eq.(14), the longer wavelength phase is only used to compute the integer values pixel by pixel to unwrap the shorter wavelength phase, thus, the longer wavelength phase noise does not significantly affect the shorter wavelength phase noise. The noise of the measurement result mostly comes from the shortest wavelength phase, thereby is very small.

- **Less sensitive to motion.** Only the shortest wavelength phase is used to compute the geometry, the rest phases are used only as references. Therefore, the sensitivity of the measurement to motion is not drastically affected by the longer wavelength fringe images acquisition. Therefore, it is less sensitive to motion comparing with those methods capturing the same number of fringe images at the same speed.

- **Robust phase unwrapping.** Unlike the traditional phase unwrapping algorithm, the phase is unwrapped pixel by pixel without accessing its neighboring pixels. Therefore, the unwrapping is much more robust, and less sensitive to noise. If one pixel is bad, it will not affect the rest.

- **Measuring arbitrary step height.** The phase is obtained pixel by pixel without using its neighborhood points, therefore, this technique measure each point independently, and any step height can be measured correctly.

- **Simultaneous multiple objects measurement.** Because this technique is a point by point measurement, all objects (no matter connected or not) within the field of view can be measured.

In the meantime, this algorithm has its shortcomings. Since it uses multiple sets of fringe images, the complete measurement speed is slower than that using a single wavelength or two wavelength technique. It should be noted that, as similar
Fig. 4. Comparison between the multiple-wavelength algorithm and the single wavelength algorithm ($\lambda_0 = 24$). (a) The result using the multiple-wavelength approach (as shown in Fig. 3(f) (b) The result using the traditional single-wavelength phase-shifting algorithm.

Fig. 5. Step height measurement. (a) Photograph of the object. (b)-(d) Shortest wavelength ($\lambda = 24$) fringe images of $I_1$, $I_2$, and $I_3$, respectively. (e) Measurement result rendered in 3D. (f) Plot of its cross section.

to other system using a digital fringe projection and phase-shifting algorithm, the sensitivity of our system depends on the system setup and the wavelength used. The major factors are: 1) camera resolution (the higher, the better); 2) projector resolution (the higher, the better); 3) camera depth bits (the more, the better); 4) Camera-projector angle (the larger, the better); and 5) shortest wavelength used (the shorter, the better).
7. CONCLUSION

This paper has presented a digital multiple-wavelength phase-shifting algorithm for 3D shape measurement. For this technique, a series of phase-shifted fringe images with a wavelength decreased by a factor of 2 from its previous wavelength ($\lambda_k = \lambda_{k-1}/2$), and a single fringe for the longest wavelength covers the whole measurement area. The phase for each wavelength $\phi_k(x,y)$ is unwrapped by referring to the unwrapped longer wavelength phase $\Phi_{k-1}(x,y)$ pixel by pixel without accessing its neighborhood pixels. The traditional phase unwrapping algorithm is not required for the longest wavelength phase since the single fringe covers the whole area. The noise level of this multiple-wavelength phase-shifting algorithm is similar to that of a single-wavelength phase-shifting algorithm with the shortest wavelength. Moreover, because only the last set of fringe images are actually used for 3D shape reconstruction, this is less sensitive to motion. Experiments demonstrated that a six-wavelength phase-shifting algorithm can be used to measure a human face satisfactorily. In addition, since the measurement is done pixel by pixel, this technique was also be used to measure multiple separate objects or arbitrary step height. Experiments have been presented to verify the performance of the proposed algorithm.
Fig. 7. Measurement result of a human face. (a) Photograph of the objects. (b)-(c) 3D result obtained by using a six-wavelength phase-shifting algorithm. (d) The phase map for the shortest wavelength ($\lambda_6 = 24$) for the six-step phase-shifting algorithm. (e)-(f) 3D result obtained by unwrapping the phase map shown in (d).

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