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A composite quality-guided phase unwrapping algorithm for fast 3D profile measurement

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Abstract

Fringe pattern profilometry (FPP) is one of the most promising 3D profile measurement techniques, which has been widely applied in many areas. A challenge problem associated with FPP is the unwrapping of wrapped phase maps resulted from complex object surface shapes. Although existing quality-guided phase unwrapping algorithms are able to solve such a problem, they are usually extensively computational expensive and not able to be applied to fast 3D measurement scenarios. This paper proposes a new quality-guided phase unwrapping algorithm with higher computational efficiency than the conventional ones. In the proposed method, a threshold of quality value is used to classify pixels on the phase maps into two types: high quality (HQ) pixels corresponding to smooth phase changes and low quality (LQ) ones to rough phase variance. In order to improve the computational efficiency, the HQ pixels are unwrapped by a computationally efficient fast phase unwrapping algorithm, and the LQ pixels are unwrapped by computational expensive flood-fill algorithm. Experiments show that the proposed approach is able to recover complex phase maps with the similar accuracy performance as the conventional quality-guided phase unwrapping algorithm but is much faster than the later. © 2012 SPIE.

Keywords

algorithm, fast, 3d, unwrapping, profile, composite, measurement, phase, guided, quality

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A composite quality-guided phase unwrapping algorithm for fast 3D profile measurement

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ABSTRACT

Fringe pattern profilometry (FPP) is one of the most promising 3D profile measurement techniques, which has been widely applied in many areas. A challenge problem associated with FPP is the unwrapping of wrapped phase maps resulted from complex object surface shapes. Although existing quality-guided phase unwrapping algorithms are able to solve such a problem, they are usually extensively computational expensive and not able to be applied to fast 3D measurement scenarios. This paper proposes a new quality-guided phase unwrapping algorithm with higher computational efficiency than the conventional ones. In the proposed method, a threshold of quality value is used to classify pixels on the phase maps into two types: high quality (HQ) pixels corresponding to smooth phase changes and low quality (LQ) ones to rough phase variance. In order to improve the computational efficiency, the HQ pixels are unwrapped by a computationally efficient fast phase unwrapping algorithm, and the LQ pixels are unwrapped by computational expensive flood-fill algorithm. Experiments show that the proposed approach is able to recover complex phase maps with the similar accuracy performance as the conventional quality-guided phase unwrapping algorithm but is much faster than the later.

Keywords: Fringe pattern profilometry, fast phase unwrapping, 3D measurement.

1. INTRODUCTION

As an effective tool for non-contact 3D shape measurement, Fringe Pattern Profilometry (FPP) has been an active area of research due to its potential application in many areas, such as automatic manufacturing, machine vision, medical services, and antiques protection [1]. A typical FPP system consists of a digital projector, a CCD camera and a computer. With FPP, the digital projector generates a group of image patterns which are projected onto the object surface to be measured. Due to the variance of the surface shape, the image patterns are distorted which are captured by the CCD camera. The surface shape information is carried by the distorted image patterns and is extracted by analysing the patterns. Image patterns are usually sinusoidal that the deformation of image patterns which due to the height distribution of object surface can be considered as the result of phase modulation. Consequently, the patterns can be described by phase maps, and the height distribution of object surface can be acquired by analysing the phase maps. During last three decades, various methods including Fourier Transform method (FT) [2] and Phase-shifting (PS) [3] method have been proposed to retrieve the phase maps. A main problem associates with phase retrieving methods is that such methods inevitably involves arctangent calculation which implies the phases retrieved are wrapped into the range $(-\pi,\pi]$ causing discontinuities on the phase maps. On the purpose of recovering the 3D shape of object, an additional process is required to recover the true phases from the wrapped. Such a process is called phase unwrapping which is a critical step in the FPP approaches.

Although phase unwrapping is rather simple in its principle, its implementation in practice is a challenging task. If the true phase is slow varying and not affected by noise, the process of phase unwrapping can be carried out using a simple unwrapping algorithm, which compares neighbouring pixels and adjusts their relative phase values by adding or subtracting integral 2π when a sudden change in neighbouring pixels is detected. However, such a phase unwrapping algorithm suffers from discontinuity or sharp change on object surfaces as wrong decision may be made regarding the addition or subtraction of 2π.

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During last three decades, intensive studies have been put in achieving reliable and accurate phase unwrapping, each having advantages and disadvantages. Huntly and Saldner [4] proposed a temporal phase unwrapping method, by which a set of fringe patterns with different frequencies are projected, resulting in a set of wrapped phase maps. The true phase map is recovered from the relationships among the wrapped phase maps. Temporal algorithms are robust in that they are able to recover complex phase maps, but they require multiple fringe patterns and thus are time-consuming which makes them have limited applications to fast measurements. Su *et al.* [5] proposed a colour-encoding method that every individual fringe on the projected image is formed with a particular colour based on an encoding scheme to identify the fringe number, which is used to unwrap the phase map. However, such a method requires colour CCD cameras implying higher cost in contrast to use of single channel CCD camera. Also colour-encoding techniques suffer from problem of colour crosstalk and leakage between different colour channels, which may greatly degrade the performance.

In order to improve time efficiency and reduce cost of unwrapping, people have introduced several methods based on single phase map such as simple path-following method [6], branch-cut method [7-8], and quality-guided flood-fill (QGFF) method [9-12] which are also known as spatial phase unwrapping methods. As a straight-forward method, the simple path-following method implements phase unwrapping following a fixed path. However, such a method is very sensitive to disturbance on wrapped phase map and not able to stop unwrapping failure forming a global error. With branch-cut methods, noise and spatial discontinuity points on the phase map are detected. Then the points are connected by curves, referred to as the cuts. When unwrapping is carried out, these cuts will behave as a blockage to prevent the path from getting through. In such a way unwrapping path will only go through smooth areas on the phase map and hence wrong decisions on phase unwrapping operation can be reduced. In contrast to simple path-following methods, branch-cut methods are more robust in terms of its accuracy performance but still have limited ability in unwrapping. With QGFF method, every pixel on the phase maps associated with a quality parameter measuring the smoothness of the pixel compared with its surrounding ones. Then, a flood-fill algorithm is employed, by which, the unwrapping process starts from the highest quality pixel to the lowest quality one. In which case, the unwrapping path can change its direction at each pixel in order to avoid the unwanted discontinuities and noise. On the other hand, flood-fill algorithm requires massive times of comparison for choosing the unwrapping direction which is not acceptable for fast measurement.

Although simple path-following methods are fast, they do not work well for complex phase maps. On the other hand, QGFF method requires massive times of comparison for choosing the unwrapping direction which is not acceptable for fast measurement. Consequently, a technique which is fast and also suitable for complex phase maps is still required. Intensive studies have been put into this field. Herráez *et al.* [9] proposes a fast group growing algorithm instead of flood-fill, which reduces comparison times for choosing the unwrapping direction and thus more time efficient. Zhang *et al.* [12]proposes a multilevel quality-guided phase unwrapping method which sets several quality value thresholds to divide a phase map into several levels. Within a same level, pixels are unwrapped by a fast scan line unwrapping scheme. Although some unwanted disturbances in phase map remain undetected, this method can effectively recover complex phase maps in real-time.

In this paper, we propose a novel technique which combines simple path-following and quality-guided method and hence enjoys the advantages of the both. In the first step, pixels on the wrapped phase map are classified into two types: the pixels corresponding to object surface and the pixels corresponding to shadows. When the object image is available, the shadow pixels can be identified by checking every pixel against a threshold; these pixels with lower intensity than the threshold are determined as shadow ones. The shadow pixels do not carry the 3D information of the object surface and hence do not need to be unwrapped. Then, we classify the pixels corresponding to object surface into two types: high quality (HQ) pixels and low quality (LQ) pixels, where HQ pixels are these with smooth phase variance and LQ pixels associate with phase discontinuities. In order to classify the HQ and LQ pixels, we use a threshold of quality value that pixels with lower quality than the threshold will be identified as LQ ones. Once the HQ and LQ pixels are identified, we propose to use a simple path-following method to unwrap HQ pixels first, and then we employ a maximum phase gradient (MPG) based QGFF method to unwrap LQ pixels. Experiments show that our algorithm is able to effectively unwrap complex phase maps with both speed and robustness ensured.

This paper is organized as follows. In Section 2, the proposed algorithm is presented. In Section 3, experiments results are demonstrated to verify the effectiveness of our approach. Finally, we conclude the paper in section 4.

2. DESCRIPTION OF THE ALGORITHM

2.1 Basic principle of spatial phase unwrapping

As mentioned above, in order to acquire the object surface shape, various phase detection techniques, such as Fourier Transform (FT) method and phase shifting (PS) method are proposed to extract the phase map $\phi_d(x,y)$ on object surface and $\phi_s(x,y)$ on reference plane from fringe patterns. Once the phase maps $\phi_d(x,y)$ and $\phi_s(x,y)$ are obtained, in order to obtain the height distribution of object surface, we calculate the phase shift $\phi(x,y)=\phi_d(x,y)-\phi_s(x,y)$.

Hence a major issue in FPP is to determine $\phi_s(x,y)$ and $\phi_d(x,y)$ based on the projected fringe patterns. However, due to the arctangent calculation, instead of true phase $\phi_s(x,y)$ and $\phi_d(x,y)$, a wrapped version of them are obtained with their value wrapped into the range $(-\pi,\pi]$. These wrapped phases, denoted by $\phi_s^r(x,y)$ and $\phi_d^r(x,y)$, are related to the true ones as follows:

$$\phi_s^r(x,y)=\left[\phi_s(x,y)\right]_{\mathrm{mod}\,2\pi} \quad (1)$$

and

$$\phi_d^r(x,y)=\left[\phi_d(x,y)\right]_{\mathrm{mod}\,2\pi} \quad (2)$$

where, $[\cdot]_{\mathrm{mod}\,2\pi}$ denotes the modular operation making the argument to be within $(-\pi,\pi]$. Phase unwrapping is such an operation that recovering the true phases $\phi_s(x,y)$ and $\phi_d(x,y)$ from $\phi_s^r(x,y)$ and $\phi_d^r(x,y)$. As we know, the reference plane is a flat board which implies $\phi_s(x,y)$ is a linear function with respect *x*. As $\phi_s^r(x,y)$ is also a linear function with respect *x* within a fringe period, and hence it is easy to be unwrapped. Therefore, in the following steps, we only consider the unwrapping of $\phi_d^r(x,y)$.

When object surface is smooth and slow varying, the true phases $\phi_d(x,y)$ should be monotonic and continuous, and in this case it can be recovered by comparing neighbouring pixels on $\phi_d^r(x,y)$ and adding or subtracting 2π when a sudden change in neighbouring pixels is detected in $\phi_d^r(x,y)$. Based on this idea, phase unwrapping can be carried out from one pixel to another following a certain path on $\phi_d^r(x,y)$. Supposing (x,y) and (x',y') are two adjacent pixels on the path, the following provides a straight-forward method to unwrap pixel (x,y) from (x',y').

$$\phi_d(x,y)=\phi_d(x',y')+\Delta\phi_d^r(x,y)+\begin{cases}-2\pi, if & \pi<\Delta\phi_d^r(x,y)\le 2\pi\\ 0, \;\; if & -\pi<\Delta\phi_d^r(x,y)\le \pi\\ 2\pi, \; if & -2\pi<\Delta\phi_d^r(x,y)\le -\pi\end{cases} \quad (3)$$

where, $\Delta\phi_d^r(x,y)=\phi_d^r(x,y)-\phi_d^r(x',y')$. $\phi_d^r(x',y')$ and $\phi_d(x',y')$ are the wrapped phase and recovered true phase at (x',y') which are known. $\phi_d^r(x,y)$ is the wrapped phase at (x,y) which is also known.

From Equation (3) we can see that phase unwrapping depends on the steps on $\phi_d^r(x,y)$. When a step on $\phi_d^r(x,y)$ of π over adjacent pixels is detected, true phase $\phi_d(x,y)$ can be recovered by adding or subtracting 2π to its existing value. However, such an approach may not work in practice, as $\phi_d^r(x,y)$ may also exhibit steps due to other reasons, such as shadows on the fringe patterns, discontinuities in object surface shape and measurement noise. These types of steps may also trigger Equation (3) and result in a wrong unwrapping operation. Due to the recursive nature of the spatial phase unwrapping algorithms, such phase unwrapping errors will propagate along the path of the unwrapping operation.

2.2 Shadow areas removal

As mentioned above, pixels corresponding to shadows do not carry any 3D information that they must be isolated from the phase unwrapping operation. To achieve this, such pixels need to be identified on the fringe patterns. Other researchers define a fringe modulation based mask map to identify the shadow areas [12]. However, such a method inevitably involves time-consuming square-root calculation for each pixel, and thus not suitable for the fast measurement. On the other hand, if an object image is available, we can easily identify the shadow areas using an intensity threshold. However, in FPP, we only have fringe patterns, from which we will recover the object image.

Assuming N-step phase shifting profilometry (PSP) is used, a series of N sinusoidal fringe patterns are projected onto the surface of the object surface, and for each step, the reflected images $d_n(x,y)$ are captured by a digital camera which are:

$$d_n(x,y) = r_d(x,y)\left[I_1 + I_2\cos\left(\phi_d(x,y) + \frac{2\pi(n-1)}{N}\right)\right] \tag{4}$$

where, $n = 1,2,...,N$, and $\phi_d(x,y)$ is the phase map which contains the object surface 3D information. $r_d(x,y)$ is the reflectivity of object surface. I_1 and I_2 are the intensity of background and fringe component respectively , which are assumed to be constant. Obviously each fringe pattern consists of two components: the background component $I_1 \cdot r_d(x,y)$ and the fringe component $I_2 \cdot r_d(x,y)\cos\left(\phi_d(x,y) + 2\pi(n-1)/N\right)$. In order to retrieve the object image, we need to keep the background component $I_1 \cdot r_d(x,y)$. Considering the phase-shift property of the fringe component, the background component can be estimated by simply averaging the N fringe patterns as follows:

$$I_d(x,y) = \frac{1}{N}\sum_{n=1}^{N} d_n(x,y) \tag{5}$$

We have the object image $I_d(x,y)$. With $I_d(x,y)$ available, we can identify the shadow areas. As reflection from object surface is much stronger than that from shadow areas. A threshold I_{th} can be used to identify the two types of pixels. The pixels with lower intensity than the threshold are considered as shadows. After all pixels checked against the threshold, we use a binary mask $B(x,y)$ to indicate the pixel corresponds to object surface or shadows:

$$B(x,y) = \begin{cases} 1 & \text{if} \quad I_d(x,y) \geq I_{th} \\ 0 & \text{if} \quad I_d(x,y) < I_{th} \end{cases} \tag{6}$$

where $B(x,y) = 1$ indicates that the pixel corresponds to object surface, and $B(x,y) = 0$ indicates that the pixel corresponds to shadows.

2.3 Quality map generation

The determination of $B(x,y)$ enable the proposed method to block all the shadow pixels from participating the phase unwrapping process. However, rough phase variances can still be observed in the areas corresponding to object surface, which may trigger wrong decision of phase unwrapping. Quality map is such a metric to evaluate the difficulties of unwrapping in terms of the smoothness of wrapped phase map. The higher quality indicates the easier for corresponding pixel to be unwrapped. As 2π discontinuities due to phase wrap also exist on $\phi_d^r(x,y)$, these discontinuities must be removed when calculate the quality map. Assuming the fringe patterns are horizontal and hence the phase increases along y direction, these intrinsic 2π discontinuities is can be removed by the following:

$$\phi_d(x,y) = \phi_d(x,y-1) + \Delta\phi_d^r(x,y) + \begin{cases} -2\pi, if & \pi < \Delta\phi_d^r(x,y) \leq 2\pi \\ 0, \ if & -\pi < \Delta\phi_d^r(x,y) \leq \pi \\ 2\pi, \ if & -2\pi < \Delta\phi_d^r(x,y) \leq -\pi \end{cases} \tag{7}$$

where, $\Delta\phi_d^r(x,y) = \phi_d^r(x,y) - \phi_d^r(x,y-1)$.

The maximum phase gradient (MPG) is a simple and effective way to evaluate the phase quality. For computational simplicity, we use the MPG at pixel (x,y) with its surrounding neighbours to calculate the quality map, that is:

$$MPG(x,y) = \max\left\{\left|\phi_d(x,y) - \phi_d(x-1,y)\right|, \left|\phi_d(x+1,y) - \phi_d(x,y)\right|, \left|\phi_d(x,y) - \phi_d(x,y-1)\right|, \left|\phi_d(x,y+1) - \phi_d(x,y)\right|\right\} \tag{8}$$

where, the value range of MPG is $0 < MPG(x,y) \leq \pi$. The larger the MPG, the lower the quality $Q(x,y)$.

2.4 High quality (HQ) and low quality (LQ) pixels identification

As indicated above, simple path following technique enjoys the advantages of simplicity and high speed, but not suitable for complex or low quality phase maps. QGFF algorithm is able to unwrap complex phase maps, but suffers from the low efficiency in terms of computational burden. In practice, it is very common that object surfaces have both smooth and rough areas, implying that $\phi_d^r(x,y)$ contains both high quality (HQ) and low quality (LQ) areas. If these two different areas on $\phi_d^r(x,y)$ can be identified, we can apply simple path following algorithm to the HQ areas and the flood-fill technique to the LQ ones, and this will lead to efficiency performance improvement. In this section we will present such a technique.

A flow-chart of our proposed method is shown in Fig.1. The first and key step is to divide $\phi_d^r(x,y)$ into HQ and LQ areas. In order to do that, we check quality values of every pixels against a threshold Q_{th}. The pixel (x,y) is considered to be of HQ if $Q(x,y) \geq Q_{th}$ and it is LQ if $Q(x,y) < Q_{th}$. The choosing of Q_{th} is a trade-off. If Q_{th} is too high, the resulting HQ areas may contain a lot of pixels with large phase variance. On the other hand, if Q_{th} is too low will result in many LQ areas and the low efficiency in recovering $\phi_d(x,y)$. In practice, for the objects we measured in our lab, a proper Q_{th} should ensure 90%-95% pixels are sorted as HQ pixels.

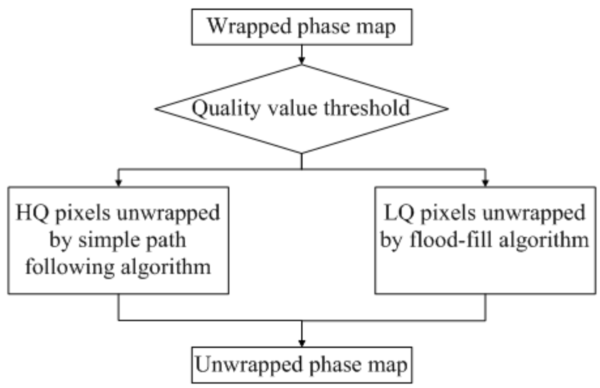


Figure 1 The flow-chart of our proposed method.

2.5 Special designed simple path following algorithm

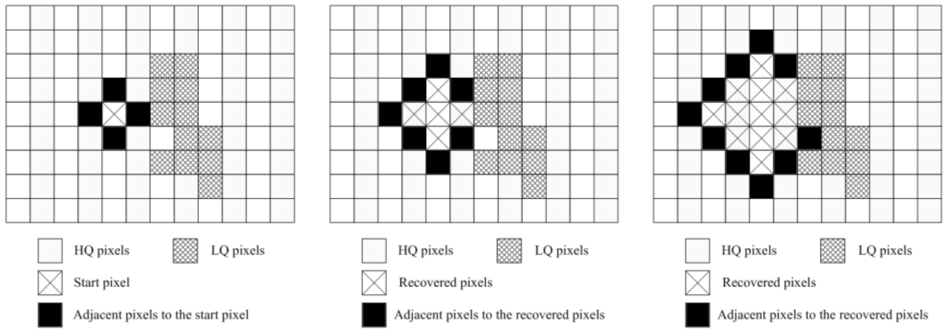
Once the HQ areas and LQ areas are identified, a special designed simple path following algorithm is applied to unwrap the HQ areas. On the purpose of tracking the status of unwrapping operation, the pixels have been unwrapped give definitions for 'recovered' and the others 'unrecovered'. This special designed simple path following algorithm is described as following:

Step 1. Choose the pixel with maximum quality value (i.e. lowest MPG) in HQ area as the start pixel, assuming that phase value of this pixel on the wrapped phase map is the same as the true phase. Mark this pixel as 'recovered'.

Step 2. Unwrap all the HQ pixels adjacent to 'recovered' pixels using Equation (3), and mark them as 'recovered'.

Step 3. Repeat Step 2 until there is no 'unrecovered' HQ area pixel left.

An example of such algorithm is shown in Fig.2.



(a) (b) (c)

Figure 2 An example of the special designed simple path following algorithm in our research, (a) step1, (b) step2 and (c) step 3.

2.6 Quality-guided flood-fill (QGFF) algorithm

After the HQ area pixels have been unwrapped, the QGFF algorithm is applied to unwrap the LQ areas. In order to clearly describe such an algorithm, let us assume that we have a cursor with its position indicating the pixel on which phase unwrapping is currently carried out:

Step 1. Find out a LQ pixel neighbouring a HQ pixel; Unwrap this pixel based on its neighbouring HQ pixel using Equation (3). Put the cursor to this point and mark the point as 'unwrapped', and then start the unwrapping process as follows.

Step 2. Check the quality value of the four pixels surrounding the cursor, that is, the pixels to the left and the right, the ones above and below; Find out the pixel with the highest quality value and move the cursor to the pixel and do unwrapping using Equations (3).

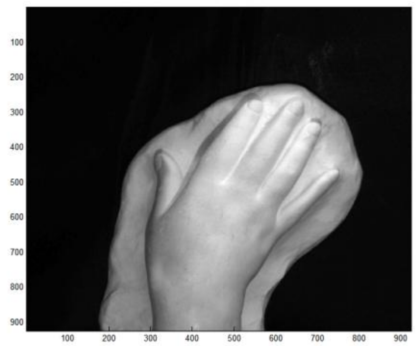
Step 3. Check the surrounding pixels around the unwrapped pixel obtained in Step 2 and select the pixel with the highest quality value and move the cursor to the pixel; Repeat Step 2 until all pixels have been unwrapped.

Unwrapping process is completed when all pixels on wrapped phase map have been unwrapped.

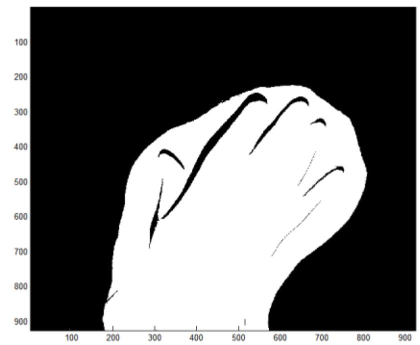
3. EXPERIMENT VERIFICATIONS

In order to demonstrate the proposed approach, we compare it with simple path-following algorithm [6] and QGFF algorithm [10]. We applied them to images acquired by a 3D shape FPP system in our laboratory. In the experiment system, the sinusoidal fringe patterns are generated by a HITACHI CP-X260 digital projector, and a Duncan Tech MS3100-RGB 3CCD digital camera is utilized to capture the images. The digital camera is placed on top of the projector with a distance of 350 mm between their lenses. The distance between the reference plane and camera lens is 895 mm. The five-step phase-shifting profilometry (5-PSP) has been applied to acquire phase information and to calculate surface height of object.

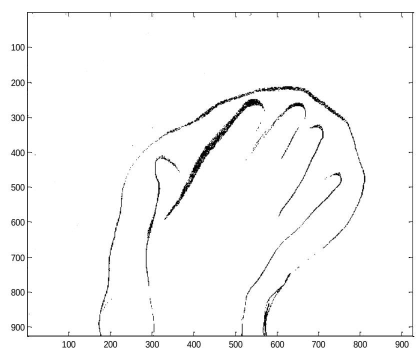
We used a plaster hand model to be the object and Fig.3(a) shows the object image which is the result of averaging 5 fringe patterns images using Equation (5). The resolution of image is 925×925 pixels. The phase shift between each step is $2\pi/5$. Fig.3(a) shows the object image. Fig.3(b) shows the mask of shadow pixels when $I_{th} = 50$, while the maximum grey value on the object image is 255. I_{th} was selected experientially as $I_{th} = 50$ can produce satisfactory results. Q_{th} is set to be 95% pixels have higher quality with. Fig.3(c) shows the identification of LQ pixels.



(a)



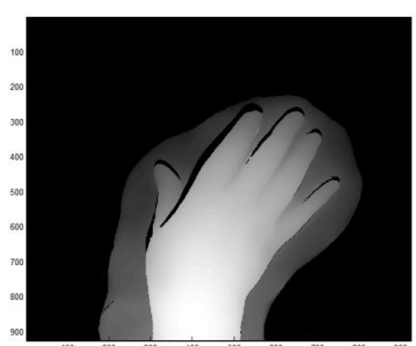
(b)



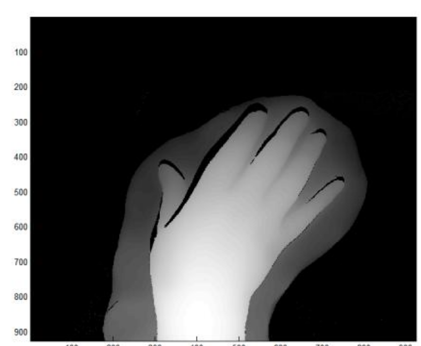
(c)

Figure 3(a) The object image. (b) The corresponding validation mask $B(x, y)$ when $I_{th} = 50$, black indicates shadow pixels, white indicates pixels corresponding to object surface. (c) The identification of LQ pixels (black).

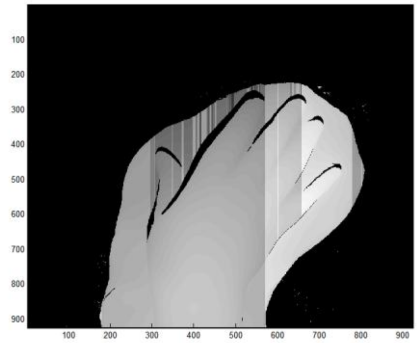
The true phase maps recovered are shown in Fig.4(a), which is in contrast to the phase maps recovered by QGFF algorithm in Fig.4(b), and simple path-following method in Fig.4(c). Note that QGFF algorithm is assumed the most robust algorithm for recovering the true phase. Fig.4(d) shows the difference of recovered phase maps between the proposed method and QGFF algorithm, implying that the two are very close to each other. Fig.4(e) shows the difference of recovered phase maps between simple path-following algorithm and QGFF algorithm.



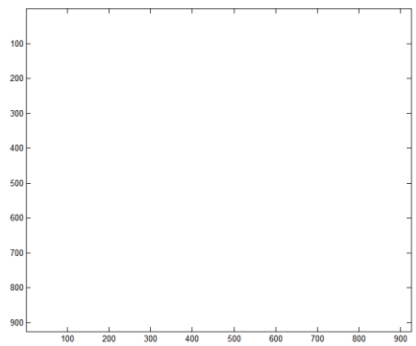
(a)

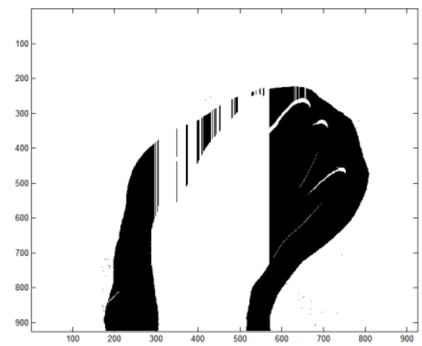


(b)



(c)

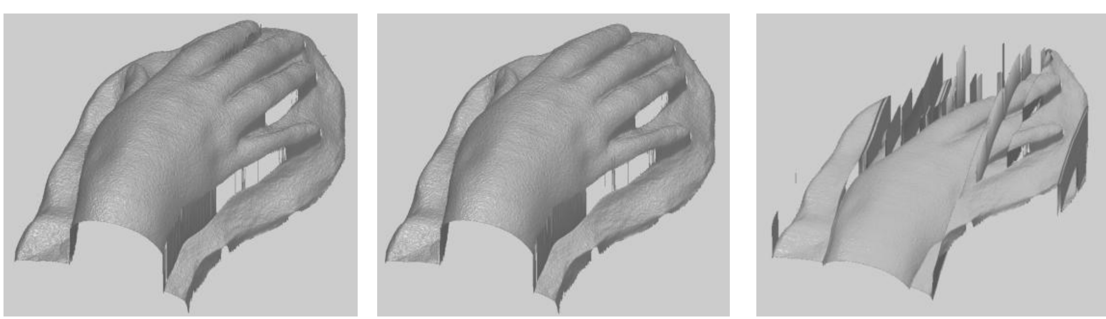




(d) (e)

Figure 4(a) Recovered phase map by the proposed method. (b) Recovered phase map by quality-guided flood-fill algorithm. (c) Recovered phase map by simple path-following algorithm. (d) The difference map between (a) and (b) with black denotes the difference. (e) The difference map between (b) and (c) with black denotes the difference.

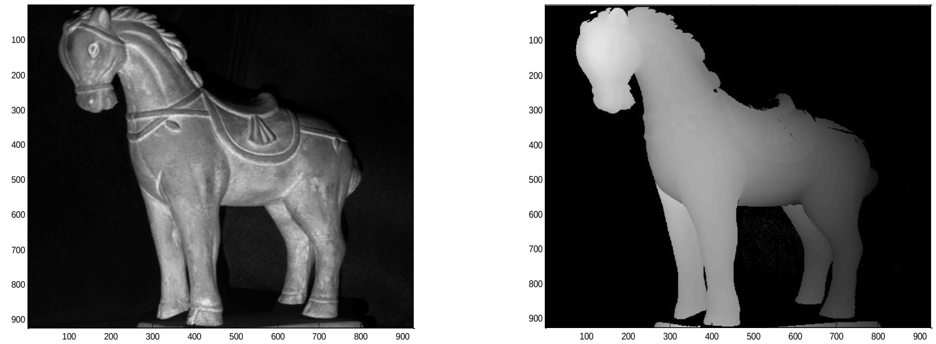
Fig.5 shows the 3D reconstruction results using the proposed approach, the QGFF algorithm, and the simple path-following algorithm. It is seen again that both the proposed technique and the QGFF algorithm can retrieve much better results than the simple path-following algorithm.



(a) (b) (c)

Figure 5 (a) 3D results by the proposed method. (b) 3D results by QGFF algorithm. (c) 3D results by simple path-following algorithm.

We also tested our proposed method using a horse statue as the target. From which, we have the same conclusion. Fig.6(a) shows the object image. Fig.6(b) shows the true phase map recovered by our proposed method. Fig.7 shows the 3D result.



(a) (b)

Figure 6 (a) The object image. (b) Recovered true phase map by our proposed method.

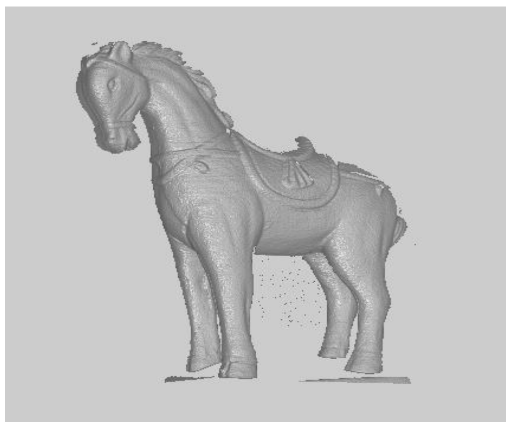


Figure 7 The 3D result using our proposed method

The comparison of phase unwrapping time between the algorithms is shown in Table 1, from which, we can clearly see that our proposed method can successfully reduce the time used for phase unwrapping in contrast to the quality-guided flood-fill.

Table 1. Comparison of unwrapping time.

Unwrapping time (ms)	Simple path-following	Quality-guided flood-fill	Proposed method
Plaster hand	106	29892	755
Horse statue	93	28241	967

The computation time was acquired by a Deltacom desktop (Intel Q9400@2.66GHz, 4 G memory in Matlab; the image size is 925 × 925 pixels

In order to figure out the reason for the efficiency improvement, we studied the number of pixels identified as LQ using the proposed method for the three object models. The LQ pixels are unwrapped by the QGFF algorithms, which will account for most the computational burden. It is seen from Table 3 that for all the three objects, only 0.2% or less are identified as LQ, which means that the number of pixels unwrapped by flood-fill algorithm is greatly reduced. Thus, the computational burden associated with our proposed method is significant lower than that of QGFF algorithm.

Table 2. Comparison of the number of pixels unwrapped by QGFF algorithm.

	Number of pixels	Percentage over the total
Plaster hand	1.97×10^3	0.230%
Horse statue	3.41×10^3	0.398%

The image size is 925×925 pixels

From Table 2, we can see that the number of pixels unwrapped by flood-fill algorithm in our proposed algorithm is greatly reduced. Thus, the computational burden associated with our proposed method is significant lower than that of quality-guided flood-fill algorithm, especially when the image size is large. With regard to experiments results, the proposed approach is able to significant reduce the computation burden.

4. CONCLUSIONS

We presented a composite quality-guided phase unwrapping algorithm for fast 3D FPP system. With the proposed approach, an object image is firstly constructed by averaging the fringe patterns acquired. Using the object image, shadow areas are identified and corresponding pixels on the unwrapped phase map are isolated from participating the phase unwrapping operation. The quality map was generated according to the MPG of pixels on the phase map. By comparing $Q(x,y)$ of each pixel to a preset Q_{th}, pixels were thus classified into HQ and LQ pixels. Then a special designed simple path following algorithm was applied to unwrap the HQ and then QGFF algorithm was applied to unwrap the LQ pixels. As demonstrated by experiment results, the proposed approach is characterized by less than 5% computational burden at image size 925×925 but is able to achieve the same level of 3D measurement robustness in comparison with QGFF algorithm.

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