A new quality map for quality-guided phase unwrapping

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A new quality map for quality-guided phase unwrapping is presented. The quality map is derived from the wrapped phase map directly and can reflect phase quality accurately. It is demonstrated that the proposed quality map is a good phase-quality indicator, with which the quality-guided unwrapping algorithm can retrieve a reliable phase profile.

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The concept of phase unwrapping of two-dimensional signals has attracted considerable interest in recent years. The areas of application include several branches of applied physics and engineering[1]. Giving a wrapped phase image of a surface profile, the task of phase unwrapping is to reconstruct the profile by adding multiples of 2π to the image. However, many factors, such as surface discontinuities, noise, undersampling or shadow, would produce unreliable phase data, which make the recovery of a true surface profile challenging. The quality–guided phase unwrapping algorithm[2] is a method to confine unavoidable errors caused by unreliable phase data to minimum area. The algorithm uses a quality map, which is an array of values that define the quality or goodness of each pixel of the given phase image, to guide its unwrapping process. The successful implementation of the algorithm largely relies on whether the quality map can truly reflect phase quality. Depending on the application, several quality maps[3−6], such as those derived from correlation coefficients, pseudocorrelation, phase derivatives variance, or fringe modulation, have been proposed in the past years.

In this letter a new quality map for quality-guided phase unwrapping is presented. The proposed quality map is a hybrid from two commonly used quality maps, the pseudocorrelation map and the maximum phase gradient map. It simultaneously measures the magnitude of the largest phase gradient and the pseudocorrelation coefficients in $l \times l$ neighborhoods of each pixel of the phase image. The new quality map is expected to reflect phase quality accurately.

The new quality map is defined by the equation

$$q_{m,n} = \max\{|\Delta^x_{i,j}|, |\Delta^y_{i,j}|\}_{(l\times l)} \times \frac{\sqrt{\left(\sum_{i=m-l/2}^{m+l/2}\sum_{j=n-l/2}^{n+l/2}\cos\phi_{i,j}\right)^2 + \left(\sum_{i=m-l/2}^{m+l/2}\sum_{j=n-l/2}^{n+l/2}\sin\phi_{i,j}\right)^2}}{l \times l}, \tag{1}$$

where the quality of the pixel (m,n) is calculated from its $l \times l$ neighborhoods. The term $\max\{|\Delta^x_{i,j}|, |\Delta^y_{i,j}|\}_{(l\times l)}$ is the maximum phase gradient at the pixel (m,n), which is defined to be the greater of the two values, $\max\{|\Delta^x_{i,j}|\}$ and $\max\{|\Delta^y_{i,j}|\}$. The two maxima are also calculated in $l \times l$ neighborhoods. The terms $\Delta^x_{i,j}$ and $\Delta^y_{i,j}$ are the partial derivatives of the phase. The terms $\phi_{i,j}$ are the wrapped phase values. The terms $\Delta^x_{i,j}$ and $\Delta^y_{i,j}$ can be computed by the formulas

$$\Delta^x_{i,j} = W(\phi_{i+1,j} - \phi_{i,j}), \tag{2}$$

and

$$\Delta^y_{i,j} = W(\phi_{i,j+1} - \phi_{i,j}), \tag{3}$$

where W is the wrapping operator that wraps all phase difference into the range $(-\pi, \pi]$. From above equations we know that the proposed quality map is directly derived from the wrapped phase map.

The new quality map can truly reflect phase quality. In the areas where discontinuities, noise and undersampling appear, and the phase data are unreliable and should be recognized in the quality map. Discontinuities and noise in the unwrapped phase must be restricted to areas of noise and true discontinuity in the profile. Such areas can be successfully identified by their low quality in the proposed quality map. The quality map also can be effectively responsive to corrupted pixels that have been corrupted by undersampling caused by abrupt changes in the true profile. In this case, such pixels are assigned low-quality values, though these pixels may have good image quality.

Two wrapped phase images, which contain boundaries of sharp discontinuities between two planar surfaces, are used to compare the reliability of the proposed quality map with that of the phase derivative variance map. The latter is generally believed as the most reliable measurement of phase quality[6]. We compute both of the quality maps in 3×3 neighborhoods of each pixel.

The two simulated wrapped images depicting wrapped phase in the range $(-\pi, \pi]$ are scaled between black and white for display. The first phase image, shown in Fig. 1, consists of two planar surfaces that have been tilted relative to one another, creating a line of shear between them. The line of shear is clearly discernible in the phase

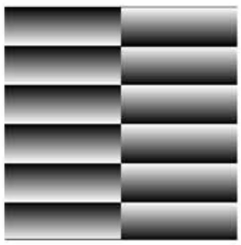

Fig. 1. The wrapped phase image of the sheared planes.

Fig. 2. The wrapped phase image of the spiral sheared planes.

image. The phase data corresponding to the two planes must be unwrapped independently without crossing the line of shear. The second wrapped phase image is shown in Fig. 2. Two planar surfaces have been tilted relative to one another, but in this case the boundary between them consists of intertwined spirals. The arms of the spirals twist around one another and the spiral shear boundaries lie between the arms. The phase data corresponding to the arms of the spirals must be unwrapped independently without crossing the shear boundaries.

In order to correctly unwrap the above wrapped phase images, a good quality map should yield low-quality values on the shear boundaries and constitute true barriers between the planes. The phase derivative variance map of the sheared planes is shown in Fig. 3(a) and the new quality map of the sheared planes is shown in Fig. 3(b). The low quality values are shown as dark pixels and the high quality values as light pixels. Three-dimensional (3D) renderings of Figs. 3(a) and (b) are shown in Figs. 3(c) and (d), respectively. The renderings have been inverted for clarity. In both cases the lines of low-quality values that separate the planes vary periodically, but the new quality map does not dip as low as the phase derivative variance map does. Hence the new quality map seems more reliable than the phase derivative variance map, though each of the two quality maps constitutes a true barrier between the planes and is successfully used to obtain the same unwrapped result as shown in Fig. 3(e).

In the case of the spiral sheared planes, it is more evident that the new quality map is superior to the phase derivative variance map. The phase derivative variance map of the example is shown in Fig. 4(a) and

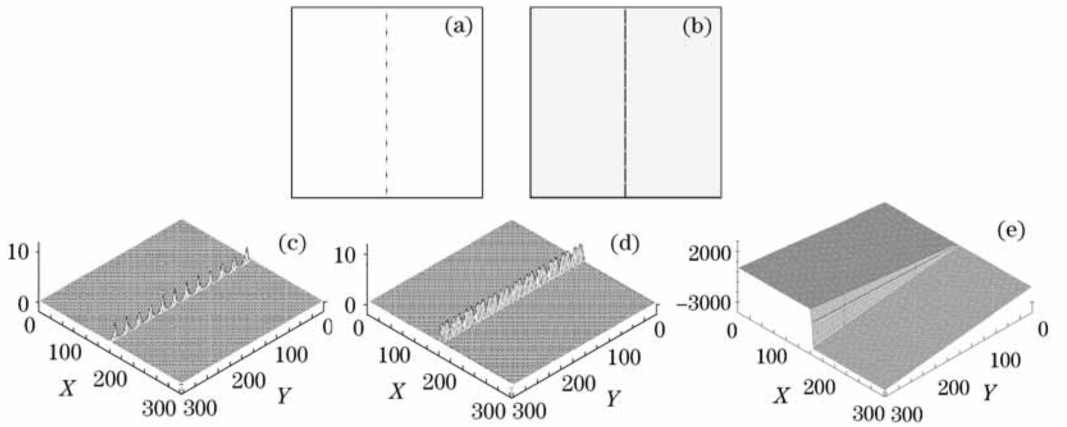

Fig. 3. (a) The phase derivative variance map of the sheared planes; (b) the proposed new quality map of the sheared planes; (c) 3D rendering of (a); (d) 3D rendering of (b); (e) result of unwrapping with the proposed new quality map.

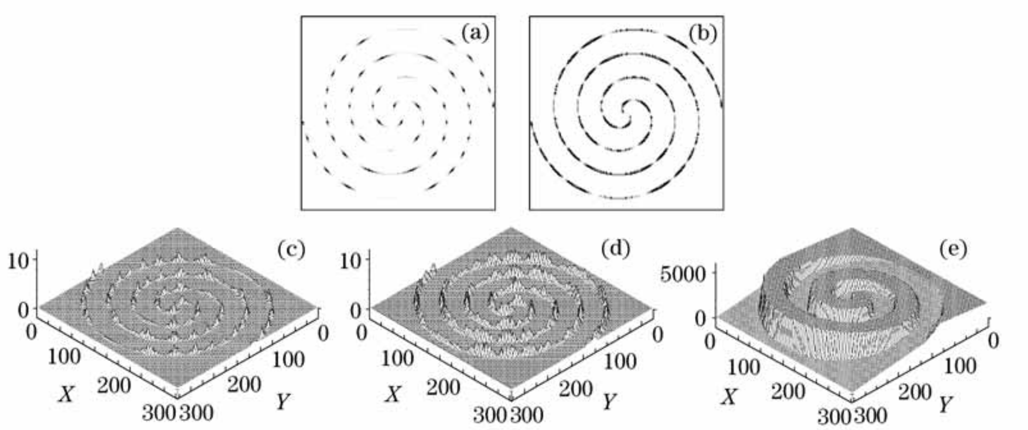

Fig. 4. (a) The phase derivative variance map of the spiral sheared planes; (b) the proposed new quality map of the spiral sheared planes; (c) 3D rendering of (a); (d) 3D rendering of (b); (e) result of unwrapping with the proposed new quality map.

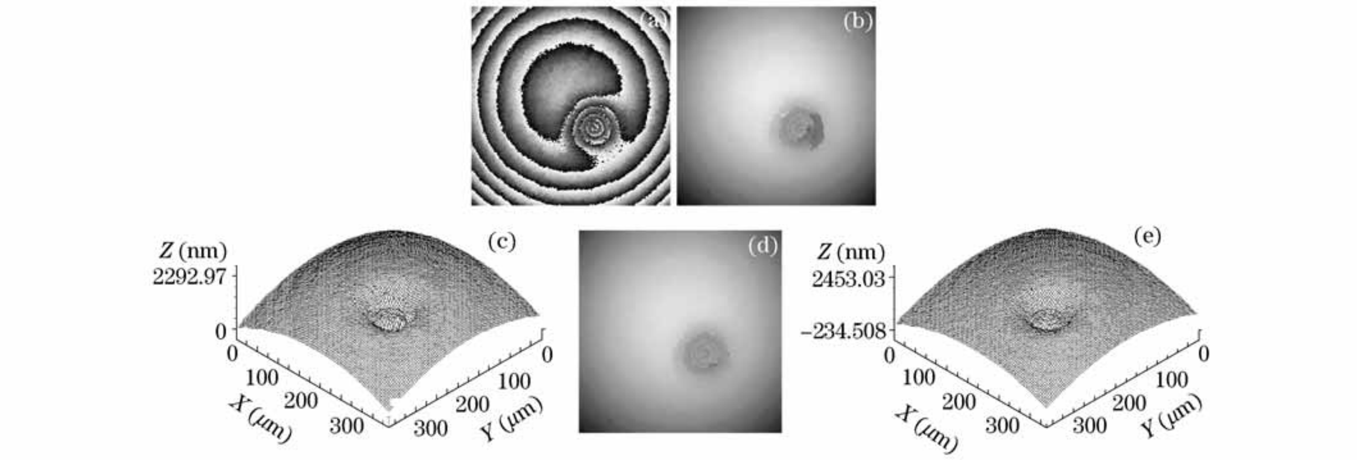

Fig. 5. Unwrapping of a wrapped phase image obtained from the measurement of an optical fiber connector endface. (a) Wrapped phase image; (b) unwrapped result by use of the quality-guided algorithm with the phase derivative variance map; (c) 3D rendering of (b); (d) unwrapped result by use of the quality-guided algorithm with the new quality map; (e) 3D rendering of (d).

the new quality map of the example is shown in Fig. 4(b). 3D renderings of Figs. 4(a) and (b) are shown in Fig. 4(c) and (d), respectively. The renderings also have been inverted for clarity. In Fig. 4(c), it can be seen that part of the low-quality line dips quite down to the level of the surrounding quality value. The line for the new quality map shown in Fig. 4(d), on the other hand, never dips down to the level of the surrounding values. Thus the new quality defines a true barrier between the planes. It can be used to guide the unwrapping path correctly. The unwrapped result is shown in Fig. 4(e). On the contrary, the phase derivative variance map cannot isolate the spiral sheared planes from one another and cannot be used as a quality map to correctly guide phase unwrapping process.

Now we present an experimental wrapped image used to illustrate the performance of the proposed new quality map. The endface of a fiber optical connector was measured. By use of four-step phase-shifting interferometry, the wrapped phase map of a section of the fiber connector endface is obtained, as shown in Fig. 5(a). As it can be seen, the wrapped phase map is corrupted by salt-and-pepper noise, especially in the area of the fiber undercut. In addition, the dense fringe in the area may cause undersampling problem. The high levels of noise and the undersampling are present in the wrapped phase image and make this image a difficult one to unwrap.

Figure 5(b) shows the unwrapped result by use of the quality-guided unwrapping algorithm with the phase derivative variance map. The corresponding 3D plot of Fig. 5(b) is shown in Fig. 5(c). It can be seen that in noisy and rapid changing part of the endface of the fiber connector, where the fiber endface lies, the algorithm generates an incorrect unwrapped region which is discontinuous with surrounding area. On the contrary, when the proposed new quality map is used, the quality-guided unwrapping algorithm copes well with the intractable wrapped data, producing a correct unwrapped result that is consistent. The unwrapped result and its corresponding 3D representation are shown respectively in Figs. 5(d) and (e).

In conclusion, we have demonstrated that a new quality map for quality-guided phase unwrapping works effectively even in the case that the phase derivative variance map fails. It is shown that the proposed quality map is more reliable than the phase derivative variance map, which is generally believed as the most reliable measure of phase quality. Hence the proposed quality map can be considered as a good phase-quality indicator, with which the quality-guided unwrapping algorithm can retrieve a reliable phase profile.

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