A New Fast Quality-Guided Flood-Fill Phase Unwrapping Algorithm

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Abstract. When unwrapping a phase of a complex wrapped phase map, there are usually phase jumps and time-consuming. The quality-guided flood-fill unwrapping phase algorithm is the most common kind of unwrapping algorithm, and the unwrapping effect is better than others, but it is spend too much time to real-time reconstruction. On the basis of quality-guided flood-fill phase unwrapping algorithm, we have improved the algorithm speed by optimizing path. This article compares the unwrapping effect and the unwrapping time of various common unwrapping methods through experiments. The experimental results show that our proposed approach has good performance.

1. Introduction

Fringe pattern profilometry is an important three-dimensional measurement method with the advantages of non-contact, low cost and high precision. This method mainly uses the phase as a feature to obtain the three-dimensional contour of the object, so we need obtaining an accurate phase value to ensure the measurement accuracy. The phase shift method [1-2] is a common phase measurement method with high accuracy, but it obtain wrapped phase only between [0, 2π). And the continuous phase information needs to be calculated by unwrapping the wrapped phase, thereby combining the inside and outside calibrating parameters of camera and projector for getting the three-dimensional contour of the object.

The current unwrapping phase algorithm is mainly divided into two types, based on the path-guided phase unwrapping algorithm and the minimum-norm phase unwrapping algorithm. Path-based phase unwrapping algorithms include the Goldstein branch cut method [3], quality-guided unwrapping phase algorithm [4], the Flynn minimum discontinuous method [5], and the regional growth method [6]. Least square method is the typical algorithm [7] in the minimal norm algorithm; it can be divided into unweighted least square method and weighted least square method.

The unwrapping accuracy and unwrapping efficiency are always the focus of the unwrapping phase research. The path-guided phase unwrapping algorithm has less computational complexity than the minimum-norm unwrapping algorithm, so the unwrapping speed is faster. The quality-guided algorithm is one of the path-guided unwrapping algorithm with the higher precision, and many scholars have conducted in-depth research on it. Miguel et al [8] proposed a robust quality-guided unwrapping algorithm, improved the function of generating the quality map, and improved the unwrapping effect, but at the same time, the amount of calculation also lead to the increase of the time consumption. Based on the quality-guided algorithm, the representation is the quality-guided flood-fill algorithm. Chen et al [9] proposed a quality-guided unwrapping algorithm based on edge detection 3D profilometry of object images; Cui et al [4] introduced a phase unwrapping algorithm that combines residual detection with the quality-guided flood-fill algorithm, and it can be used to measure
discontinuous 3D objects. Although the above two algorithms are ideal for unwrapping effects, they all have the drawback that they are consume too much time.

In summary, the current unwrapping algorithms still have the problem that the unwrapping accuracy and the unwrapping efficiency cannot be taken into account. This paper improved the quality-guided flood-fill algorithm for the problems of the complex unwrapping path and the time-consuming. Compared with the traditional quality-guided algorithm, this algorithm has a more reasonable unwrapping path and greatly improves the unwrapping speed. In addition, this paper compares this algorithm with several common unwrapping algorithms based on path-guided algorithms in unwrapping effect and unwrapping time. The experimental results show that the proposed method has better performance than other algorithms.

2. Description of the Proposed Algorithm

2.1. Quality Maps

The application of the quality-guided flood fill unwrapping algorithm is very extensive, and many researchers have studied it. It is a continuous path unwrapping algorithm that always unwraps along points with relatively high quality. Unwrapping errors usually occur at low quality pixels, so the robustness of the method is better.

The quality-guided flood fill unwrapping algorithm is based on a quality map to determine the path of unwrapping. Common quality maps that can be used for phase unwrapping are PSD (pseudo-correlation) quality map, PDV (phase derivative variance) quality map, and MPG (maximum-phase gradient) quality map. It is generally believed that the quality map calculated by the PDV is better evaluate the quality of the pixel and more accurately in unwrapping the phase [10]. The point \((m, n)\) in the PDV quality map can be defined as (1).

\[
q(m, n) = \frac{1}{k \times k} \left[ \sum_{i=m-k/2}^{m+k/2} \sum_{j=n-k/2}^{n+k/2} (\nabla x_{i,j} - \nabla x_{m,n})^2 \right]^{1/2} + \left[ \sum_{i=m-k/2}^{m+k/2} \sum_{j=n-k/2}^{n+k/2} (\nabla y_{i,j} - \nabla y_{m,n})^2 \right]^{1/2}
\] (1)

According to equation (1), the quality value of each pixel in the image can be calculated and the PDV quality map of the image can be generated.

2.2. Quality-Guided Flood Fill Unwrapping Algorithm

In order to solve the problem of phase jump and noise quality-guided flood-fill algorithm is proposed. It has a high unwrapping precision. The conventional quality-guided flood fill unwrapping steps are as follows.

- Firstly, find out the pixel with the highest quality value on the quality map, place the cursor on it, and mark it as “unwrapped”.
- Check the quality parameters of four pixels surrounding the cursor. Find out the point which the unwrapped quality value is the highest, unwrap it to the point where the cursor is, mark it as “unwrapped”, and move the cursor to it.

The unwrapping of pixel A with to to pixel B can be performed according to the following equation.

\[
\phi_d(x, y) = \begin{cases} 
\phi_d(x, y) - 2\pi & \nabla \varphi(x, y) \leq -\pi \\
\phi_d'(x, y) & -\pi \leq \nabla \varphi(x, y) \leq \pi \\
\phi_d(x, y) - 2\pi & \nabla \varphi(x, y) \geq +\pi 
\end{cases}
\] (2)

Where \(\nabla \varphi(x, y) = \varphi(x-1, y) - \varphi(x, y)\), \(\phi_d'(x, y) = \varphi(x-1, y) + \varphi(x, y) - \varphi(x-1, y)\)

- Repeat step 3 until all points are marked as unwrapped.
2.3. Proposed Algorithm
This method improves the quality-guided flood-fill algorithm. In high quality areas, it can multiple pixel at the same time instead of only unwrapping the cursor. Make unwrapping phase more flexible and faster. The specific steps are as follows.

● First find the pixel with the highest quality value in the quality map, place the cursor on it, and mark it as unwrapped.
● Then check the pixel above and below the point where the cursor is located. If its quality value is higher than a certain threshold, it is unwrapped according to (1). When the surrounding unsolved points are all judged, move the cursor to the quality. The point with the highest value, and if the point is not unwound, the point is unwound.
● When a point around the point has been unwound but the pixel in the picture has not been completely unwrapped, proceed from the point where the cursor is located, and find the nearest unwrapped point by its quality guide, and move the cursor to this point.
● Repeat steps 2 and 3 until all points are unwound.

3. Experiments and Results Analysis
In order to verify the performance of the proposed algorithm, it was compared with several common unwrapping algorithms. The real data and simulated data were used to unwrapping experiment by the MATLAB program. Then the evaluating performance of each algorithm from the unwrapping effect and the unwrapping time respectively. The test images included computer-generated cosine fringe pattern and an analog phase map with gradients and shear planes in different directions, and apple and dolls images captured Daheng MER-132-30UC digital camera with fringe patterns which are generated by a Philips PPX4010 digital projector.

Figure 1 shows the wrapped phase images of the test images. (a), (b), (c) and (d) are computer generated cosine fringe patterns, analog phase diagrams with gradients and shear planes in different directions, and apple, doll image obtained by a digital camera respectively. In the following figures, (a), (b), (c) and (d) are the unwrapping effects images of these images under different unwrapping algorithms.

![Figure 1](image_url)

**Figure 1.** Wrapped phase images (a) Cosine fringe pattern (b) Analog phase diagrams (c) Apple (d) Doll

The simple path unwrapping algorithm (SPUA) uses the phase relationship of neighboring pixels to unwrap the pixels row by row or column by column. Its advantage is that the speed is particularly fast, but error propagation is unavoidable because there is no path guidance. Many researchers use their fast unwrapping speed to combine it with other unwrapping algorithms to improve the real-time of unwrapping. Figure 2 shows the unwrapping effect of the test graph using the simple path algorithm. It can be seen from the figure 2 that a little complex images appear obvious errors.

![Figure 2](image_url)

**Figure 2.** SPUA (a) Cosine fringe pattern (b) Analog phase diagrams (c) Apple (d) Doll
Chen et al [9] proposed a fast quality-guided flood-fill unwrapping algorithm (FQGFF). After generating the quality map, the image is divided into several areas according to the quality map. Then quality-guided flood fill unwrapping algorithm is used to solve with low quality areas, and non-path guidance algorithm is used to the phase smoothing regions. This algorithm has good effect of unwrapping, but the rate of unwrapping is very slow. Especially when the image is enlarged, the speed of unwrapping is multiplied.

![Figure 3. FQGFF](a) Cosine fringe pattern (b) Analog phase diagrams (c) Apple (d) Doll

Cui et al [4] introduced a phase unwrapping algorithm combining residual detection with quality-guided flood-fill unwrapping algorithm (RQFF), which can be used to measure discontinuous 3D objects. The algorithm has good unwrapping effect, but its robustness is poor. For complex images, the speed of entangling will slow down.

![Figure 4. RQFF](a) Cosine fringe pattern (b) Analog phase diagrams (c) Apple (d) Doll

It is an algorithm combining residual detection, edge detection and quality-guided flood-fill unwrapping algorithm (REQG). It is more effective and practical. However, the algorithm is too complex resulting in poor robustness. Figure 5 are results of unwrapping effect of this method.

![Figure 5. REQG](a) Cosine fringe pattern (b) Analog phase diagrams (c) Apple (d) Doll

Figure 6 is unwrapping effective images of the proposed algorithm (PA). This algorithm utilizes the advantages of quality-guided flood-fill unwrapping algorithm, and the phases of its unwrapping images are smooth and continuous. It can be seen from the figure 6 that this algorithm is suitable for both simple pictures and complex pictures.
Figure 6. Proposed algorithm (a) Cosine fringe pattern (b) Analog phase diagrams (c) Apple (d) Doll

Table 1 shows the comparison of execution times among several algorithms. From the data in the table, SPUA and REQG have the fastest unwrapping speed. However, from the above-mentioned, we can see that their unwrapping accuracy are not high. Although FQGFF, RQGFF have high precision in unwrapping, it can be seen from the table 1 those algorithms need too much time. The proposed algorithm has a good unwrapping effect, fast execution time and strong robustness. It performance is more balance than others.

| Fringe pattern(s) | Analog phase(s) | Apple(s) | Doll(s) |
|-------------------|----------------|----------|---------|
| SPUA              | 1.917586       | 2.108232 | 1.687214| 1.779945|
| FQGFF             | 359.4231       | 585.552284| 1212.77 | 1215.15273|
| RQGFF             | 10.772531      | 9.8948   | 20.19141| 20.101023|
| REQG              | 1.3456465      | 1.244514 | 15.50504| 15.687063|
| PA                | 150.561231     | 180.236546| 565.5624| 552.32565|

4. Conclusion
This paper presents a fast and reliable phase unwrapping algorithm. In this paper, the quality guided unwrapping algorithm is improved. Firstly, the PDV quality map is generated. Then, starting from the highest quality pixel in the quality map, the cursor is placed on this pixel and the quality value of the surrounding points is judged, if its quality better than the threshold, we unwrapping phase of the pixel. After finished unwrapping the pixels around the cursor, the cursor is moved to the pixel with the highest quality value in its neighboring pixels. If no pixels are better than the threshold, we should unwrap the pixel with the highest quality value. When all the pixels are marked as “unwrapped”, the unwrapping is completed. According to contrastive experiments, it shows that proposed algorithm has better performance in unwrapping speed and unwrapping effect than others.

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6. Reference
[1] Zhao H, Diao X, Jiang H and Li X 2017 High-speed triangular pattern phase - shifting 3d measurement based on the motion blur method Optics Express. 25 (8) 9171
[2] Yu S, Zhang J, Yu X, Sun X, Wu H and Liu X 2018 3D measurement using combined Gray code and dual-frequency phase-shifting approach. Optics Communications. 413 283 - 90
[3] Goldstein R M, Zebker H A, Werner C L 1988 Satellite radar interferometry: two dimensional
phase unwrapping Radio Science. 23 (4) 713 - 20

[4] Cui H 2011 Reliability-guided phase-unwrapping algorithm for the measurement of discontinuous three-dimensional objects Optical Engineering. 50 (6) 409 - 21

[5] Flynn T J. 1997 Two-dimensional phase unwrapping with minimum weighted discontinuity Journal of the Optical Society of America A. 14 (10) 2692 - 2701

[6] Fornaro G, Sansosti E 1999 A two-dimensional regions growing least squares phase unwrapping algorithm for interferometric SAR processing Geoscience & Remote Sensing IEEE Transactions on. 37(5) 2215 - 2226

[7] Min M A, Zhang D S 2002 Least-square method for phases unwrapping Optical Technology. 28 (1) 94 - 96

[8] Arevalillo-Herráez M, Villatoro F R, Gdeisat M A 2016 A Robust and Simple Measure for Quality-Guided 2D Phase Unwrapping Algorithms IEEE Transactions on Image Processing A Publication of the IEEE Signal Processing Society. 25 (6) 2601- 2609

[9] Chen K, Xi J, Yu Y 2012 Fast quality-guided phase unwrapping algorithm for 3D profilometry based on object image edge detection IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops 64 - 69

[10] Lu J, Li J, Wang C 2015 Precise and fast phase unwrapping algorithm based on structured edges Optoelectronics Laser. 1 122 - 9