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Application of global phase filtering method in multi frequency measurement

Abstract

In reverse engineering, reconstruction of 3D point cloud data is the key step to acquire the final profile of the object. However, the quality of 3D reconstruction is influenced by noise in the three-dimensional measurement. This paper aims to tackle the issue of removing the noisy data from the complex point cloud data. The 3D-GPF (Three Dimensional Global Phase Filtering) global phase filtering method is proposed based on the study of phase filtering method, consisting of the steps below. Firstly, the six-step phase shift profilometry is used to obtain the local phase information, and encoding the obtained phase information. Through the global phase unwrapping method, the global phase can be acquired. Secondly, 3D-GPF method is used for the obtained global phase. Finally, the effect of 3D reconstruction is analyzed after the global phase filtering. Experimental results indicate that the noisy points of three-dimensional graphics is reduced 98.02%, the speed of 3D reconstruction is raised 12%. The effect of the proposed global phase filtering method is better than DCT and GSM methods. It is high precision and fast speed, and can be widely used in other 3D reconstruction application.

Keywords

global, phase, filtering, application, method, measurement, multi, frequency

Disciplines

Engineering | Science and Technology Studies

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Application of global phase filtering method in multi frequency measurement

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Abstract: In reverse engineering, reconstruction of 3D point cloud data is the key step to acquire the final profile of the object. However, the quality of 3D reconstruction is influenced by noise in the three-dimensional measurement. This paper aims to tackle the issue of removing the noisy data from the complex point cloud data. The 3D-GPF (Three Dimensional Global Phase Filtering) global phase filtering method is proposed based on the study of phase filtering method, consisting of the steps below. Firstly, the six-step phase shift profilometry is used to obtain the local phase information, and encoding the obtained phase information. Through the global phase unwrapping method, the global phase can be acquired. Secondly, 3D-GPF method is used for the obtained global phase. Finally, the effect of 3D reconstruction is analyzed after the global phase filtering. Experimental results indicate that the noisy points of three-dimensional graphics is reduced 98.02%, the speed of 3D reconstruction is raised 12%. The effect of the proposed global phase filtering method is better than DCT and GSM methods. It is high precision and fast speed, and can be widely used in other 3D reconstruction application.

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1. Introduction

3D shape measurement based on fringe pattern projection is widely used in the manufacturing inspection, medical sciences, reverse engineering, etc. It has the advantages of fast speed, high accuracy, easy to detect free-form surface, real 3D scene pick-up [1], etc. However, the quality of 3D image reconstruction often suffers from the influence of noise associated with the measurement. Therefore, image denoising has been an active topic of research and a few approaches have been proposed in order to improve the quality of the 3D images, such as the following:

DCT (Discrete Cosine Transformation) method: Yang, et al. [2] proposed a method using three-dimensional block matching to remove Gauss noise of image. Danielyan, et al. [3] demonstrated that the Block-Matching 3D (BM3D) filter can significantly improve the quality of two-photon fluorescence images. Kang, et al. [4] studied the statistical characteristics of self-similarity presented a two-stage 3D filtering algorithm to eliminate the noise in images. However, these DCT algorithms are of local pixel level in nature where the statistical features of the global image are not considered.

GSM (Gaussian Scale Mixtures) method: Theis, et al. [5] presented a probabilistic model for natural images based on mixtures of Gaussian scale mixtures and a simple multi-scale representation. Goossens, et al. [6] proposed a statistical model for image restoration in which neighborhoods of wavelet subbands are modeled by a discrete mixture of linear projected Gaussian Scale Mixtures (MPGSM). This algorithm described the correlation between the shape of the edge and neighborhood coefficients in the wavelets, but the local structures cannot be well described.

NLMID (Non-local Means Image Denoising) method: Wu, et al. [7] presented a structure-tensor based on non-local mean (NLM) denoising technique that can effectively reduce noise in MRI data and improve tissue characterization. Hou, et al. [8] proposed a programmable GPU (graphic processor unit) based on fast NLM filter for 3D ultrasound speckle reduction. Jiang, et al. [9] proposed an improved bilateral filtering algorithm based on the signal structure. Yu, et al. [10] introduced a 3D space-time non-adaptive pre-filtering approach in airborne radar. The speed of 3D measurement can be improved with this method. However, the phase filtering method cannot retain the phase information effectively when removing the noise, and a lot of useful phase information can get lost.

In conclusion, it's very necessary to look for an algorithm which considers the statistical features of the global image, involves low computational complexity and has excellent denoising performance. Based on the former research of our laboratory [11], we propose to employ a 3D-GPF (Three Dimensional Global Phase Filtering) global phase filtering method for solving the challenging problem of noise removal. The proposed method uses the six-step phase shift profilometry (PSP) method to obtain the local phase information. The proposed method can be considered as a new NLMID method. In contrast to existing techniques, the proposed is advantageous in a number of aspects. The proposed is better than the local phase filtering methods in its capability of eliminating the noisy disturbance. And the method proposed can protect the structure information of the original image. Also, with the proposed method the speed of 3D measurement can be improved. The proposed method is suitable to other 3D reconstruction methods, such as multiple frequency method as well as the gray (code) method.

2. The unwrapping principle of multi frequency phase

A fringe pattern with its light intensity exhibiting sinusoidal variance can be expressed as follows:

$$I(x) = a(x, y) \sin(\varphi(x, y)) \quad (1)$$

In actual measurement, due to the influence of background light, the intensity of the observed can be written as:

$$I_r(x, y) = b(x, y) + a(x, y) \sin(\varphi(x, y) + \delta(x, y)) \quad (2)$$

Where $b(x, y)$ is the background intensity, $a(x, y)$ is the intensity modulation, $\delta(x, y)$ is phase shift value. For the six-step PSP, six image patterns are projected, as shown by the following:

$$I_{rk}(x, y) = b(x, y) + a(x, y) \sin(\varphi(x, y) + \frac{\pi \times k}{6}), k = 0, 1, \dots, 5 \quad (3)$$

And the wrapped phase value $\varphi(x, y)$ can be calculated by:

$$\varphi(x, y) = \arctan \frac{I_{r3}(x, y) - I_{r5}(x, y)}{I_{r4}(x, y) - I_{r1}(x, y) + (I_{r3}(x, y) - I_{r5}(x, y))} \quad (4)$$

Where $\varphi(x, y)$ is the wrapped phase ranging from $-\pi$ to $+\pi$ with 2π discontinuities. In order to recover the 3D shape, the global phase is required and given by the following [12]:

$$\varphi_G(x, y) = \varphi_i(x, y) + 2\pi \times M(x, y) \quad (5)$$

Where $\varphi_G(x, y)$ is the global phase, $\varphi_i(x, y)$ is the local phase. $M(x, y)$ is the code of the point (x, y) , which can be calculated from the previous work in our lab [11,12]. If only a single fringe stripe is used, $\varphi_G(x, y) = \varphi_i(x, y)$ and $M(x, y) \equiv 0$, and phase unwrapping is not needed. However, for multiple fringe stripes, $M(x, y)$ is not always 0. When fringe patterns are projected with three wavelengths, i.e., λ_1 , λ_2 and λ_3 . The two patterns with wavelength λ_1 and λ_2 can generate an equivalent pattern with the longer wavelength λ_{12} ; similarly, λ_2 and λ_3 can generate the longer equivalent wavelength λ_{23} . These two equivalent wavelengths λ_{12} and λ_{23} can also generate the even longer equivalent wavelength λ_{123} . These equivalent wavelengths λ_{12} , λ_{23} and λ_{123} can be calculated by:

$$\lambda_{12} = \left| \frac{\lambda_1 \times \lambda_2}{\lambda_1 - \lambda_2} \right|, \lambda_{23} = \left| \frac{\lambda_2 \times \lambda_3}{\lambda_2 - \lambda_3} \right|, \lambda_{123} = \left| \frac{\lambda_{12} \times \lambda_{23}}{\lambda_{12} - \lambda_{23}} \right| \quad (6)$$

In order for the measurement to cover the whole area of interest, the equivalent wavelength λ_{123} should be larger than the number of pixels perpendicular to the fringe strips in the fringe patterns, that is, $\lambda_{123} \geq W$, where W denotes the number of horizontal pixels of the projector (for the case of vertical fringe strips) or the number of vertical pixels (for horizontal fringe stripes).

For each λ_{123} , there are $\lambda_{123} / \lambda_{12}$ discontinuities on the phase map of the pattern with the wavelength λ_{12} , and there are $\lambda_{123} / \lambda_{23}$ discontinuities on the phase maps of the wavelength λ_{23} . In order words, the phase value of the pattern of wavelength λ_{12} can be divided to $\lambda_{123} / \lambda_{12}$ parts by the discontinuities. Similarly, the phase value of the pattern with wavelength λ_{23} can be divided into $\lambda_{123} / \lambda_{23}$ parts. So there are altogether $(\lambda_{123} / \lambda_{12}) \times (\lambda_{12} / \lambda_1)$

discontinuities for the pattern with wavelength λ_1 . Therefore, when these three fringe patterns are projected onto a point (x, y) , six phases $\varphi_1(x, y)$, $\varphi_2(x, y)$, $\varphi_3(x, y)$, $\varphi_{12}(x, y)$, $\varphi_{23}(x, y)$, $\varphi_{123}(x, y)$ can be obtained, based on which $M(x, y)$ can be determined by:

$$M(x, y) = \begin{cases} \text{int}\left(\frac{\varphi_{123}(x, y)}{2\pi} \times \frac{\lambda_{123}}{\lambda_j}\right) \times \frac{\lambda_j}{\lambda_i} + \text{int}\left(\frac{\varphi_j(x, y)}{2\pi} \times \frac{\lambda_j}{\lambda_i}\right), \varphi_i(x, y) \neq 2\pi \text{ and } \varphi_j(x, y) \neq 2\pi \text{ and } \varphi_{123}(x, y) \neq 2\pi \\ \text{int}\left(\frac{\varphi_{123}(x, y)}{2\pi} \times \frac{\lambda_{123}}{\lambda_j}\right) \times \frac{\lambda_j}{\lambda_i} + \text{int}\left(\frac{\varphi_j(x, y)}{2\pi} \times \frac{\lambda_j}{\lambda_i}\right) - 1, (\varphi_i(x, y) = 2\pi \text{ or } \varphi_j(x, y) = 2\pi \text{ and } \varphi_{123}(x, y) \neq 2\pi \\ \text{int}\left(\frac{\varphi_{123}(x, y)}{2\pi} \times \frac{\lambda_{123}}{\lambda_j} - 1\right) \times \frac{\lambda_j}{\lambda_i} + \text{int}\left(\frac{\varphi_j(x, y)}{2\pi} \times \frac{\lambda_j}{\lambda_i}\right), \varphi_i(x, y) \neq 2\pi \text{ and } \varphi_j(x, y) \neq 2\pi \text{ and } \varphi_{123}(x, y) = 2\pi \end{cases} \quad (7)$$

Where for $\varphi_1(x, y)$, $i = 1, j = 12$; for $\varphi_2(x, y)$, $i = 3, j = 23$; for $\varphi_3(x, y)$, its value can be calculated from λ_{12} and λ_{23} , so $i = 2, j = 12$ or $i = 2, j = 23$.

With the method described above, the global phase maps can be recovered for the surfaces with discontinuities or sharp changes in their shape.

3. The filtering principle of global phase

The global phase recovery is influenced by color, and shape of object surface, as well as background light, and so the recovered global phase will not be not uniformly increasing line over x . Let us consider an example for the measurement of a plaster and models shown in Fig. 1(a). One of images from the six-step PSP is shown in Fig. 1(b). The local phase and the global phase of the 512 line in Fig. 1 are shown in Fig. 2 and Fig. 3 respectively. It is seen that the global phase contains many random noisy points. In order to ensure the accuracy and reliability of 3D measurement, these points must be removed.

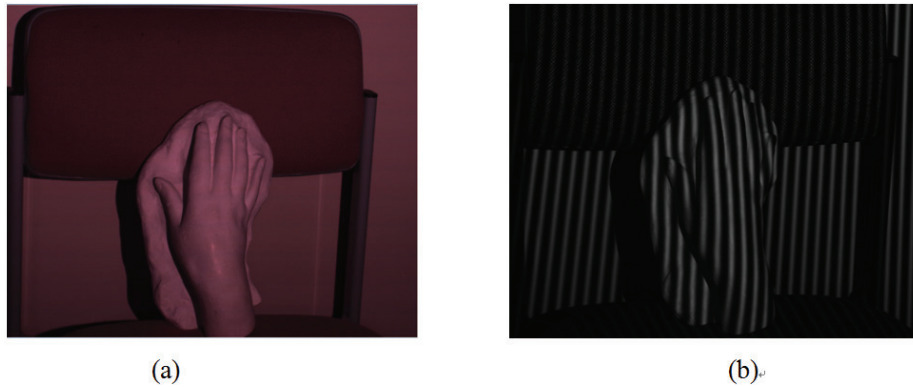


Fig. 1. Protecting the six steps PSP with one wavelength onto a fingerprint. (a) The fingerprint to be measured. (b) One of images from the six steps PSP with one wavelength.

Slope filtering method is a commonly used method to make the phase a linear increasing function. However, the values of the slope may change over different measurement points. A method for the difference of adjacent slope is proposed to filter the global phase. Firstly, the line slope of the adjacent points is calculated to obtain the absolute subtraction's result between the two slopes. If the obtained results are less than the threshold value, the line of the three points is smooth; otherwise, there is a noise at least in the three points. Secondly, some points conform to the above rules are searched, searching the adjacent points before and after the

point, if the front point is a breakpoint, in front of all the breakpoint will be set to the noisy points. If the back point is a breakpoint, from the point before the breakpoint, searching some new points which conform to the above rules. Finally, based on the new points, searching more points which meet the rules, until all the points be searched. The judging criterion is that when the number of the breakpoint is less than or equal to the number of the noisy points, the curve appears breakpoints, and then a new datum point need to be found. The proposed method to filter the global phase using different slops over adjacent points is based on the continuous conditions (Eq. (8) below) and smooth conditions (Eq. (9) below), described respectively by the following:

$$\lim_{x \rightarrow x_1^+} f(x) = \lim_{x \rightarrow x_1^-} f(x) \quad (8)$$

and

$$\lim_{x \rightarrow x_1^+} f'(x) = \lim_{x \rightarrow x_1^-} f'(x) \quad (9)$$

The specific process of the global phase filtering is as follows.

Let us assume that the resolution of the image is N by M pixels (i.e., N rows and M columns, each line of the image has M pixels). For the consecutive natural numbers $x_1, x_2, \dots, x_m, y_1, y_2, \dots, y_m$ is their reflection. According to the continuous conditions and smooth conditions, the slope of two adjacent points (k and j) must be calculated, it can be written as:

$$K = \frac{y_k - y_j}{x_k - x_j} \quad (10)$$

The processing points are discrete points, so we must change the continuous conditions and smooth conditions based on the value of the slope between two adjacent points. In order to access the smoothness of the points, we should calculate the slops of two adjacent pairs of two adjacent points. In other words, for the three consecutive points i, j , and k , the two slopes are:

$$K_1 = \frac{y_j - y_k}{x_j - x_k}, \quad K_2 = \frac{y_i - y_j}{x_i - x_j} \quad (11)$$

According to the rules of the smooth conditions, these three points are considered as smooth if $|K_1 - K_2| \leq \varepsilon$, where ε is the threshold for decision making. If $|K_1 - K_2| > \varepsilon$, the three points will be considered as a noisy group, as at least one point among the three points contains noise. When the noisy points are eliminated, the continuous conditions can be defined. Assume that the resolving power of the image is N by M pixels, M noise phase values need to be removed in each row. X is the horizontal ordinate of these phase points; it changes from 1 to M. Y is the phase value. Theoretically, Y should be an increasing linear function. However, due to the background interference and other reasons, there are a lot of noisy points in the Y, the noisy part of Y is scattered data points, and the normal part is still local linear increasing function. Normally, X should be increasing (decreasing), and the increased (decreased) value is a constant, it can be expressed as:

$$x_j - x_k \equiv a \quad (a \text{ is a constant}) \quad (12)$$

Now we applied the above to the phase map in Fig. 3, and the results are shown in Fig. 4. It is clear that the noisy points in Fig. 3 are effectively eliminated.

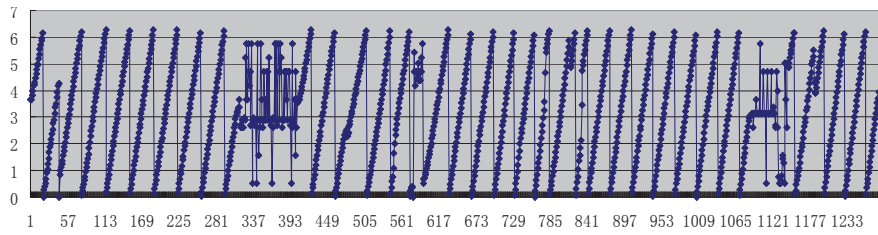


Fig. 2. The partial phase diagram of the line 512

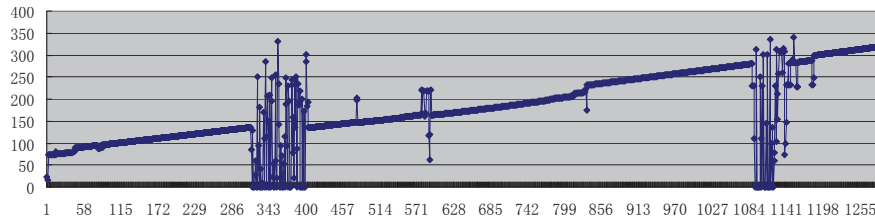


Fig. 3. The global phase diagram of the line 512

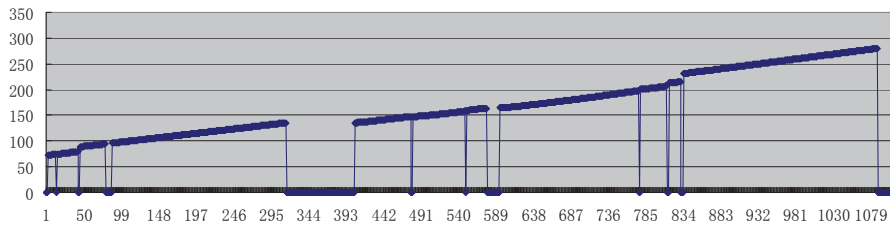


Fig. 4. The denoising global phase diagram of the line 512

4. Experiments

In order to clearly show the performance of the proposed denoising method, let us take a segment of the phase map obtained from Fig. 1 for the 26th fringe strip, as shown in Fig. 5. Without using the proposed method, the phase diagram contains many noisy points as shown in Fig. 5(a). After the global phase filtering, most of noisy points have been removed; as witnessed by the phase map shown in Fig. 5(b). Also, we construction the 3D shape based on the two phase maps respectively. Figure 6(a) shows the 3D reconstruction is very poor without using the proposed method. With the global phase filter, the 3D reconstruction of the plaster hand model is much better as shown in Fig. 6(b).



Fig. 5. A cycle's phase of the encoded point $M = 26$. (a) The phase diagram before removing the noisy points. (b) The phase diagram after removing the noisy points.



Fig. 6. The effect of 3D reconstruction. (a) The effect of 3D reconstruction without global phase filter. (b) The effect of 3D reconstruction after global phase filter.

To further verify the effectiveness of this method, the statistical data is collected to measure the performance of 3D reconstruction by means of the number of the noisy points and the speed of 3D reconstruction. The results for the case in Fig. 6 are shown in Table 1. It is clear that the number of 3D noisy points can be significantly reduced by the proposed method. The speed of 3D reconstruction is also increased.

Table 1. the number of noisy points and the speed of 3D reconstruction comparison

	the number of the noisy points	the speed of 3D reconstruction(in second)
without global phase filter	958	1.53
with the global phase filter	19	0.98

5. Conclusions

We proposed a new denoising approach for the global phase map for 3D profilometry based on digital projection. In contrast to existing techniques, the proposed is advantageous in a number of aspects:

- 1) Better denoising effect: based on the global phase, the global phase filtering method is proposed in this paper, it has better effect than the local phase filtering method, and it can effectively eliminate the noisy disturbance.
- 2) Effectively retained the available phase information: for the existing phase filtering methods, a lot of useful phase information is also removed in removing noisy points, the method in this paper can retain the phase information effectively when removing all the noisy signals.
- 3) High speed: the number of the noisy points is less than other filtering methods, so the speed of 3D measurement can be improved.
- 4) Suit to different 3D reconstruction methods: the proposed phase filtering method is based on the absolute phase value, so the proposed method is suitable to other 3D reconstruction methods, such as multiple frequency method as well as the gray (code) method.

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