Optics and Laser Technology 121 (2020) 105781

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

3D measurement method based on S-shaped segmental phase encoding

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HIGHLIGHTS

- A new approach named S-shaped segmental phase encoding is proposed.
- The method can expand the range of code words by a segmentation mechanism.
- The fringe order judgment accuracy can be guaranteed by Gray code.
- Experimental results demonstrated the high accuracy of our method.

ARTICLE INFO

Keywords:
Fringe projection profilometry
3D measurement
Phase encoding
Gray code

ABSTRACT

Phase-based encoding has good immunity and robustness due to its insensitivity to ambient light, camera noise, and surface reflectance of measured objects. However, the number of code words is limited using traditional phase encoding method. In order to solve this problem, this paper proposes a new approach named S-shaped segmental phase encoding for 3D measurement. Specifically, by using a segmentation mechanism, the proposed method can, firstly, expand the range of code words whose number is limited using traditional phase encoding method. Secondly, the measurement accuracy can be improved. In this paper, Gray code is used to encode the phase encoding segment number, such that the fringe order judgment accuracy can be guaranteed. The experimental results demonstrated more accurate and efficient 3D shape measurement than the traditional methods, especially regarding the measurement of complex and isolated objects.

1. Introduction

Due to its advantages of non-contact, low cost and high resolution [1–5], fringe projection profilometry (FPP) has been widely applied in many fields, such as industrial production and detection, robot vision, space remote sensing, medical diagnosis, social security, and three-dimensional (3D) measurement. In FPP, temporal phase unwrapping is an essential procedure to recover an unambiguous absolute phase even in the presence of discontinuities or spatially isolates surface [6]. Phase-shift methods play a dominant role due to its high attainable measurement accuracy, spatial resolution, and data density [7]. Existing approaches for 3D measurement can be divided into two categories: intensity-based and phase-based encoding fringe.

Among intensity-based method, Gray code is a typical method, which is a binary cyclic code. Bergman [8] proposed the Gray code plus phase-shift technique, which in turn projects Gray code fringe patterns and phase shifting patterns onto the measured object. Mambou [9] proposed a non-binary sequence equalization structure based on Gray code prefix [10]. Porras-Aguilar [11] proposed a method which generates grayscale coded patterns based on the traveling salesman problem. Falaggis [12] proposed a grayscale structured light encoding system, which can obtain the absolute phase in combination with the Fourier transform method or phase measurement deflection. However, studies have shown that phase encoding method is inherently better than the Gray code method, phase encoding method is less sensitive to object surface contrast, ambient light, and camera noise, because this method uses phase instead of intensity to determine the code words.

Phase-based method has good immunity and strong robustness due to their insensitivity to ambient light, camera noise, and the surface reluctance of measuring objects. Therefore, the phase-based encoding fringe has aroused the interest of experts. Wang [13] proposed a stepped phase encoding fringe method in which two sets of fringes are needed to complete the measurement: sinusoidal fringes and phase encoding fringes.

If encoding phase is quantified into large levels for more code words, the difference between adjacent quantized phase will be too small to guarantee the correct decoding, because of the system nonlinearity and defocusing. In order to increase the reliability of absolute

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https://doi.org/10.1016/j.optlastec.2019.105781
Received 9 May 2019; Received in revised form 7 August 2019; Accepted 19 August 2019
Available online 30 August 2019

phase retrieval with a large number of code words, Zheng [14] presented a novel phase encoding method which uses six additional fringe patterns to generate more than 64 unique code words. Huang [15] proposed that two initial phases should be preset to the linear phase-modulation term and frequency-modulation term of the frequency-modulated grating. Moreover, an integer was added to match the optimized grating based on Ikeda's [16] method. Zeng [17] proposed the stair phase encoding fringe, which can enlarge the number of code words. However, the fringe order needs to be corrected. Chen [18] proposed a quantized phase encoding and connected region labeling method for measuring complex objects. This method can expand the number of fringe periods without adding other fringe patterns, but it still has a small number of fringe periods. At the same time, the larger the number of cycles, the more complicated the algorithm is and more calculation is required. Wang [19] proposed an enhanced phase encoding method to expand the number of code words. For the same case, fewer fringe patterns are needed in comparison with previous method. Wang [20] proposed a segmented quantization phase encoding and decoding method that does not reduce the difference between adjacent quantized phase values or increase the quantization levels. However, the method's algorithm is complicated. Su [21] proposed a coded phase unwrapping algorithm, which encodes the fringe order by a unique phase to improve the speed of temporal phase unwrapping algorithms. Xu [22] used triangular wave fringes and new phase encoding strips to increase the original absolute phase from 2π to 10π, leading to much fewer projection patterns than before and making it suitable for rapid measurement. Zhou [23] proposed color fringe patterns are generated by encoding with sinusoidal fringe and phase encoding fringe patterns in red and blue channels to reduce the projection fringes. However, the color coupling between channels seriously affects measurement accuracy. Above all, the existing phase encoding method face two challenges, as follows: (1) Errors appear when complex surfaces are measured without correction. (2) The error rate of the solving fringe order increases as the fringe frequency increases.

Therefore, some researchers have also developed several composite phase shifting schemes for absolute phase retrieval with even less projected patterns, which the fringe order information is carefully designed and embedded to conventional phase-shifting patterns to reduce pattern number. Liu [24] proposed a novel dual-frequency pattern that can overcome the major shortcomings of conventional spatial phase unwrapping such as phase jumping and discontinuities. However, the period of the low frequency fringe must be increased for the measurement of a higher step object. Zuo [25] presented a bi-frequency tripolar pulse-width-modulation method to achieve 3D shape of complex surface, this method can achieve high-speed measurement when the projector is in slight defocus. Zuo [26] describes an 3D real-time shape measurement technique using newly developed high-speed 3D vision system. It employs only four projection fringes to realize full-field phase unwrapping in the presence of discontinuous or isolated objects. Although the measurement speed of the above methods is fast, their measurement accuracy is not high enough. The proposed method is slow in measuring speed, but the sinusoidal fringe frequency is high, and measurement accuracy is similar to the temporal phase unwrapping method. And then, at the same frequency, the number of fringes is not much compared with temporal phase unwrapping method.

Therefore, this paper proposes an S-shaped segmental phase encoding method for 3D measurement. The proposed method encodes the number of phase-encoding segments with Gray code and increases the number of phase encoding code words by segmentation. Meanwhile, the S-shaped design provides constraints for the judgment of the fringe order, reduces the error rate, and improves the measurement accuracy. Furthermore, experiments are used to evaluate the effects on 3D measurement and demonstrate the superiority of the proposed method compared with existing method.

Because phase encoding method is robust to the surface contrast, ambient light, and camera noise, the code words are embedded into the phase and used to determine the fringe order. However, its accuracy would reduce when dealing with a large number of code words, because of the system non-linearity and defocusing. To solve this problem, segmenting code words is proposed, but there is a problem how to solve the segment connection. So, using Gray code to connect the segmental phase encode is naturally thought, because Gray code is a typical method, which is a binary cyclic code. One binary code is only one bit different from its neighbor codes, which minimizes the chance of decoding mistakenly. The advantages of using Gray code to connect the segmental phase encode are as follows: (1) Gray code method is relatively mature for solving the fringe order edge errors and easy to correct. (2) When phase encoding method solves the fringe order, burrs are easy to appear at the jump point, which is not easy to correct. So, the proposed method has a strong ability of anti-interference.

The remainder of this paper is structured as follows. Section 2 describes the principle of the S-shaped segmental phase encoding method. Section 3 demonstrates the proposed method via experiments. Section 4 summarizes and concludes the paper.

2. Principles

2.1. Measurement system

The measurement system included a projector, a camera and computer (Fig. 1).

Fringe patterns are generated by the computer and projected onto the surface of the object by the digital projector. The fringe is modulated by the surface of the object, and the deformed fringe is recorded by the CCD camera. Phase field extraction and phase unwrapping are performed by the computer, and the absolute phase value is also obtained. Then, the height of the object's surface is obtained using the following phase-height equation:

$$h = \frac{L\Delta\varphi}{2\pi f_0 d + \Delta\varphi} \tag{1}$$

where d is the distance between the camera and the projector, L is the distance between the camera and the reference plane and f_0 is the sinusoidal fringe frequency on the reference plane.

2.2. S-shaped segmental phase encoding method

The higher the frequency of the sinusoidal fringe, the higher the measurement accuracy. However, the number of pixels in a single step width is correspondingly reduced as the number of steps increases. In this case, the edge of the phase encoding fringe commonly has over-smoothed or blurry regions, which makes judgment of the fringe order difficult and prone to error. As a result, finding out the discontinuity

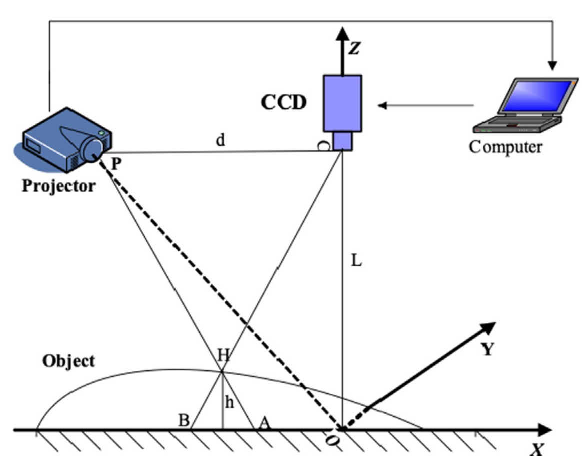

Fig. 1. 3D measurement system.

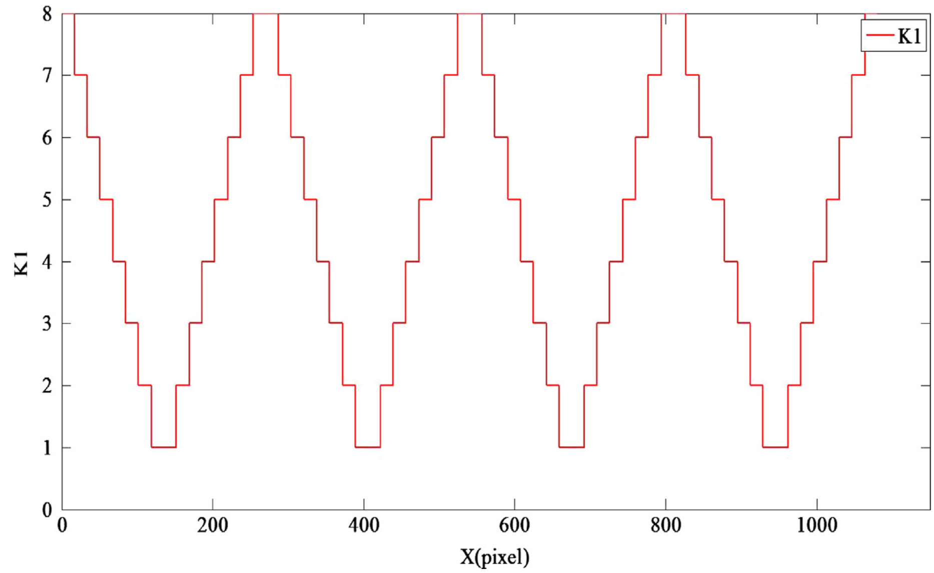

Fig. 2. One row cross of the phase encoding fringe order.

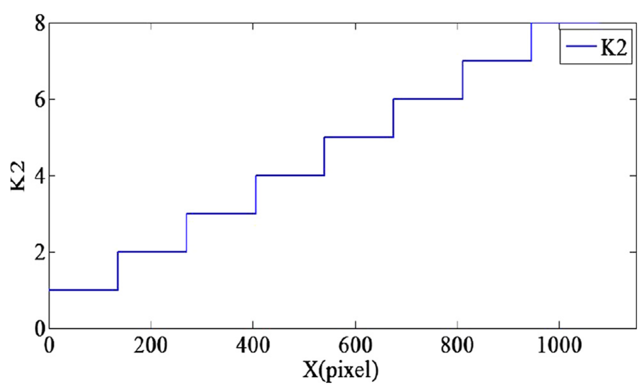

Fig. 3. One row cross of the segmentation order.

Table 1
Gray code coding.

First fringe	0	0	0	0	1	1	1	1
Second fringe	0	0	1	1	1	1	0	0
Third fringe	0	1	1	0	0	1	1	0

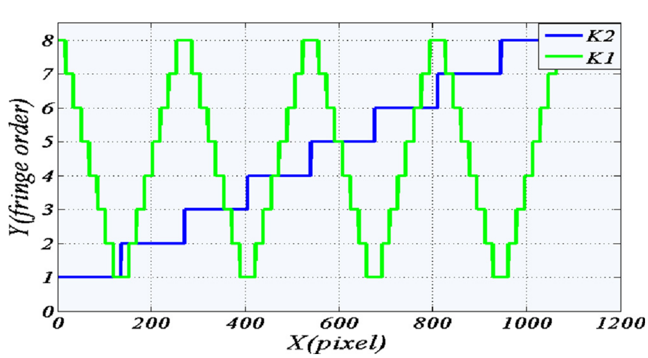

Fig. 4. Fringe order K-value map corresponding to Figs. 2 and 3.

point accurately and judging the fringe order accurately will be difficult. In this paper, code words designed are embedded into the sinusoidal fringe patterns. Next, the generation of the code sequence CW will be introduced [18]. The codes are divided into two groups: odd and even. In this paper, the quantized level $m = 8$ is set as an example. If the Gray code order is odd, phase codes will be designated as "87654321". If the Gray code order is even, phase codes will be designated as "12345678". Therefore, the code sequence is as follows:

$$CW = ''87654321123456788765432112345678\cdots\cdots'' \tag{2}$$

The designed encoding step phase φ^scan be described as follows:

$$\varphi^s(x, y) = \begin{cases} \pi - CW\,[floor\,(x/p)]^*2\pi/p, & floor\,(x/(m^*p)) \in even \\ -\pi + CW\,[floor\,(x/p) + 1]^*2\pi/p, & floor\,(x/(m^*p)) \in odd \end{cases} \tag{3}$$

where x is the pixel in the horizontal direction of the projector, y is the pixel in the vertical direction of the projector, m represents the number of code words encoded for each segment or quantized level, p is the number of pixels in one period of the fringe, $floor(x)$ is the largest integer not greater than x, and CW(x) returns the k_{th} code of CW.

In order to obtain the segmentation phase encoding fringe order, the segmented step phase must be extracted from the modulated segmented phase encoding fringes. The segmented phase encoding fringe patterns are generated by embedding the coding step phase into the phase shifting sinusoidal fringes using the following equation:

$$I_n(x, y) = \alpha(x, y) + \beta(x, y)\cos[\varphi^s(x, y) + \delta_n] \tag{4}$$

$$\delta_n = 2\pi(n - 1)/N \tag{5}$$

where $I_n(x,y)$ represents the intensity of the n_{th} fringe pattern, $\alpha(x,y)$ represents the average intensity, $\beta(x,y)$ represents the intensity modulation, and N represents the number of fringe patterns. Then, following the projection operation and the recording of fringe patterns using the CMOS camera, the encoding step phase of the measured object is calculated using the equation:

$$\varphi^s(x, y) = \arctan\left[\sum_{n=1}^{N} I_n(x, y)\sin(\delta_n)/\sum_{n=1}^{N} I_n(x, y)\cos(\delta_n)\right] \tag{6}$$

Since the calculated segmentation step is a decimal, it is quantized into an integer by using the following equation:

$$C(x, y) = round\,[m \times (\varphi^s(x, y) + \pi)/2\pi] \tag{7}$$

Finally, the phase encoding fringe order of the transformed segment is calculated by the following equation:

$$K1(x, y) = R[C(x, y)] \tag{8}$$

where $R[x]$ returns the fringe order corresponding to the round quantized coding phase and $K1$ represents the phase encoding fringe order.

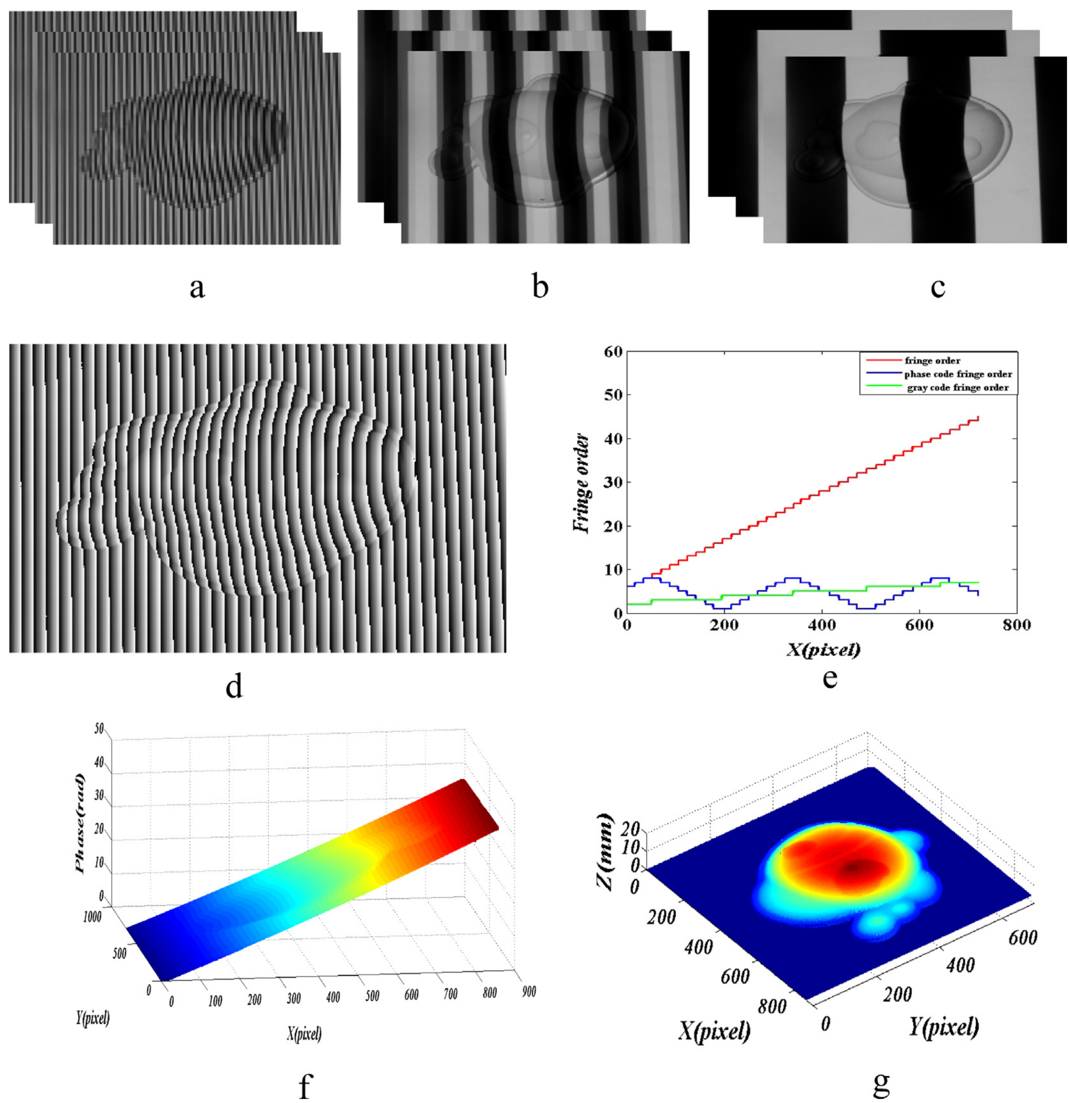

Fig. 5. 3D measurement of complex objects. (a) Sine fringe patterns, (b) phase encoding fringe patterns, (c) Gray code fringe patterns, (d) wrapped phase pattern, (e) one row cross of the fringe order, (f) absolute phase, (g) 3D measurement result.

2.3. The Gray code encoding method

In order to ensure that the wrapped phase and fringe order have a one-to-one correspondence during the process of unwrapping, the phase encoding fringe order must be connected. In this paper, the segmentation order is obtained by using the Gray code decoding.

Taking the three-bit Gray code as an example to illustrate the Gray code principle. The corresponding Gray code sequence is G_1 (00001111), G_2 (00111100), G_3 (01100110). The coding rules for the three-bit Gray code are shown in the following Table 1.

Gray code is a binary code with a low bit error rate. The Hamming distance is 1, that is, there is only a 1-bit difference between adjacent code words, so the fringe boundary error of different code words can be greatly reduced. Since the decoding requires a decimal fringe order instead of a binary number in the Gray code pattern, accurate decoding can be achieved using the following equations:

$$\begin{aligned} B_1 &= G_1 \\ B_2 &= B_1 \oplus G_2 \\ B_3 &= B_2 \oplus G_3 \end{aligned} \tag{9}$$

where G_n represents the code value of the Gray code, B_n denotes its corresponding binary code encoding value, and $\oplus$ denotes exclusive OR.

Then, the binary code is converted to decimal code to obtain the fringe order using the following equation:

$$K2 = \sum_{i=1}^{3} B_i 2^{3-i} + 1 \tag{10}$$

where $K2$ represents the decoding value of the Gray code, that is, the segmentation order.

2.4. Fringe order algorithm

The order $K1$ of the phase encoding fringe is obtained through the phase encoding fringe patterns. The segmentation order $K2$ is obtained through the Gray code fringe patterns. In order to obtain the continuous fringe order K, it is necessary to make a one-to-one correspondence between the fringe order and the wrapped phase. Therefore, based on $K1$ and $K2$, the designed algorithm using the following equation is proposed to solve the fringe order K in this paper:

$$K = \begin{cases} K2 \times m + 1 - K1, & K2 \in odd \\ (K2 - 1) \times m + K1, & K2 \in even \end{cases} \tag{11}$$

where arbitrary integer m is set as the quantized level, $K1$ represents the phase encoding fringe order, and $K2$ represents the segmentation

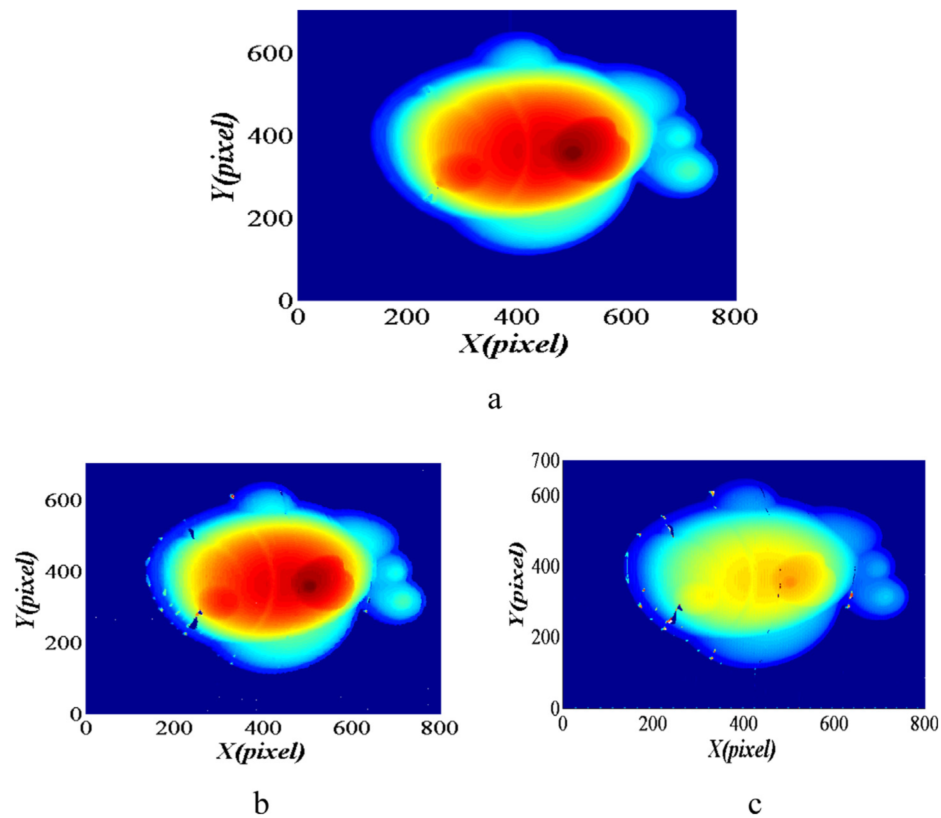

Fig. 6. Results of complex object measurement without correction: (a) proposed method, (b) traditional phase encoding method, (c) Gray code method.

order.

In order to obtain fringe order K, phase encoding fringe order K1 must be connected as upward stairs. As shown in Fig. 4, When segmentation order K2 is odd, K1 is downward stairs. When K2 is even, K1 is upward stairs. So, the Eq. (11) is proposed.

Then, the continuous phase value of the fringe pattern is obtained by using the following phase solution equation:

$$\Delta\varphi(x, y) = \phi(x, y) + 2 \times K \times \pi \tag{12}$$

where $\Delta\varphi(x, y)$ represents the continuous phase difference of the point corresponding to the object surface image and the reference plane image, and $\phi(x, y)$ represents the wrapped phase.

3. Experiment

The measurement system included a Digital Light Processing (DLP) projector (Light Crafter 4500), a Complementary Metal Oxide Semiconductor (CMOS) camera (DH-HV1351UM) and a computer. The resolution of the projector and camera were 1024×768 and 1028×1024, respectively. The values of L and d were obtained by calibration. Three step phase shifting algorithm is used in our proposed method, which need three shifting fringe patterns with high frequency projected. Therefore, three sinusoidal phase shifting fringe patterns are used to solve the wrapping phase, three phase code patterns are used to solve the phase-encoding fringe order K1, and three Gray code patterns are used to solve the segmentation order K2. The sinusoidal fringe period was set to 64, and the phase encoding was set to 8 for each segment of the code words.

A complex surface is defined as an object having discontinuities or isolated surfaces. The proposed method was tested by 3D measurement of three objects: (1) a fish with a complex surface which is explained discontinuous surfaces or surfaces with drastic height changes, (2) complex isolated objects which included a white fish and blue eggplant, and (3) standard block.

Fig. 5 shows the results of the fish measurement. Fig. 5(a–c) show one of the sine fringe patterns of the fish, the phase encoding fringe patterns of the fish and the Gray code fringe patterns of the fish, respectively. Fig. 5(d) shows the wrapped phase pattern obtained by Eq. (4). Fig. 5(e) shows one row cross of the fringe order (red line), the phase encoding fringe order (blue[1] line) and the segmentation fringe order (green line). Fig. 5(f) shows the absolute phase of the measured object. A 3D reconstruction of the fish is shown in Fig. 5(g).

The fish was also measured by Wang's [11] and Bergman's [6] method to facilitate comparison. Fig. 6(a) shows the result obtained by the S-shaped segmental phase encoding method proposed in this paper. Fig. 6(b) shows the result obtained by the traditional phase encoding method (proposed by Wang) and Fig. 6(c) shows the result of the Gray code method (proposed by Bergman). As shown in Fig. 6(b–c), there are some errors, especially in Fig. 6(c), which implies that the proposed method is more robust than other existing method during the measurement process. Due to the results shown in Fig. 6(c) being poor, this paper only discusses the measurement results shown in Fig. 6(a) and (b). Careful comparison shows that the overall surface reconstruction in Fig. 6(a) is more smooth and delicate. In fact, there is a small gap between the fish's eyes and the back bulge in the fish. Fig. 6(a) shows the result of this gap more clearly. Therefore, the experiment proves that the proposed method is more robust and precise than existing method.

To further demonstrate the feasibility of measuring complex, isolated, and differently-colored objects, a white fish and blue eggplant were measured. Fig. 7(a–c) show sine fringe patterns of complex isolated objects, phase encoding fringe patterns of complex isolated objects, and Gray code fringe patterns of complex isolated objects, respectively. Fig. 7(d) shows the wrapped phase pattern. Fig. 7(e) shows one row cross of the fringe order (red line), the phase encoding fringe

[1] For interpretation of color in Figs. 5–8, the reader is referred to the web version of this article.

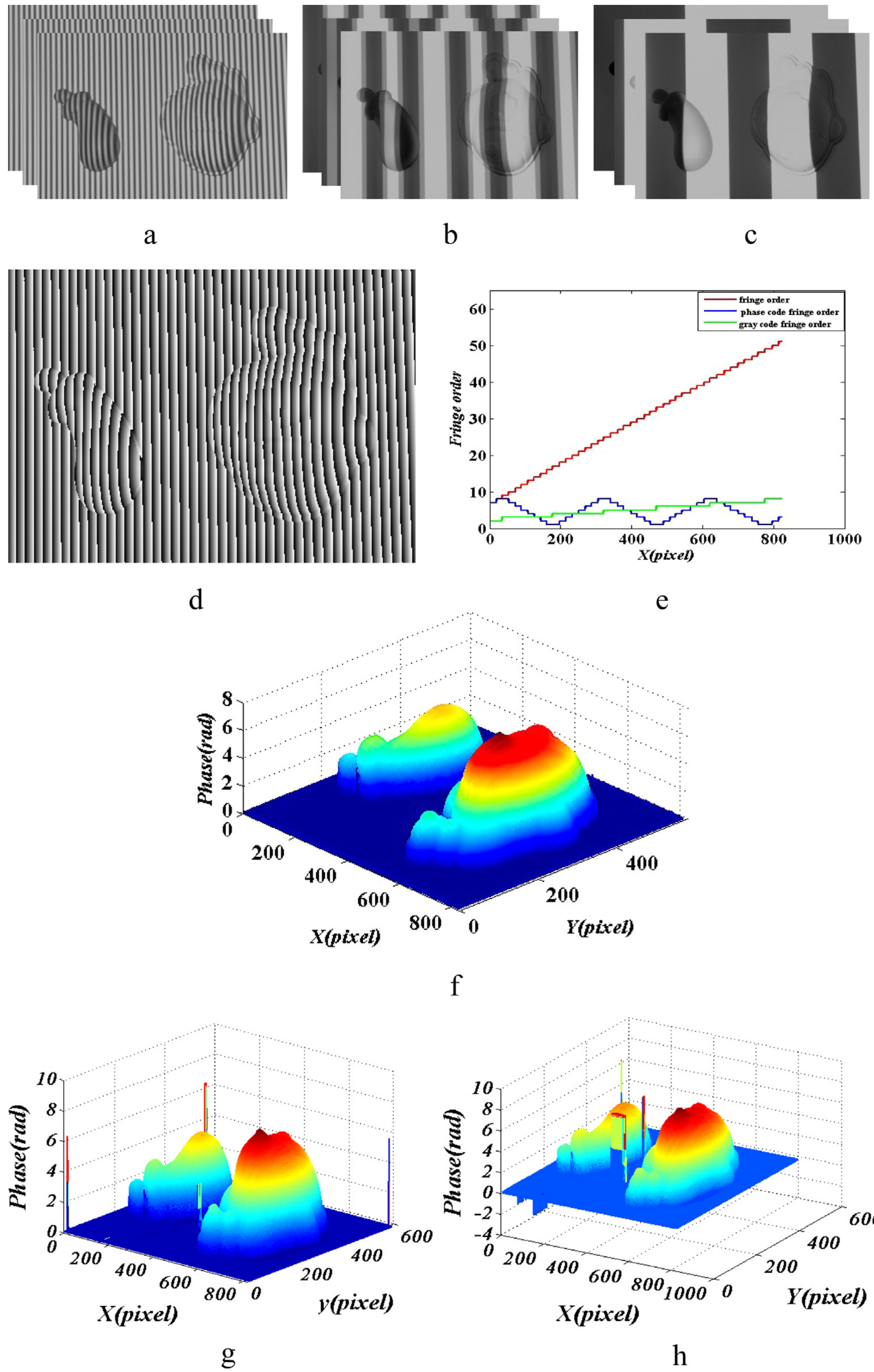

Fig. 7. 3D measurement of complex isolated objects: (a) sine fringe patterns, (b) phase encoding fringe patterns, (c) Gray code fringe patterns, (d) wrapped phase pattern, (e) one row cross of the fringe order, (f) 3D measurement result of proposed method, (g) 3D measurement result of traditional phase encoding method, (h) 3D measurement result of Gray code method.

order (blue line) and the Gray code fringe order (green line). Fig. 7(f–h) shows the 3D measurement results for isolated objects. Fig. 7(f) shows the result is obtained by the S-shaped segmental phase encoding method. Fig. 7(g) shows the result is obtained by the traditional phase encoding method (proposed by Wang) and Fig. 7(h) shows the result of the Gray code method (proposed by Bergman). As shown in Fig. 7(g), there are some of the errors, due to the system non-linearity and defocusing. Fig. 7(h) shows 3D result of Gray code method, where obvious errors are revealed. From the results, the 3D result by the proposed method has a smooth surface without bulging or pitting. The experiment results indicate that the proposed method is more robust.

In order to analyze the measurement accuracy of the proposed

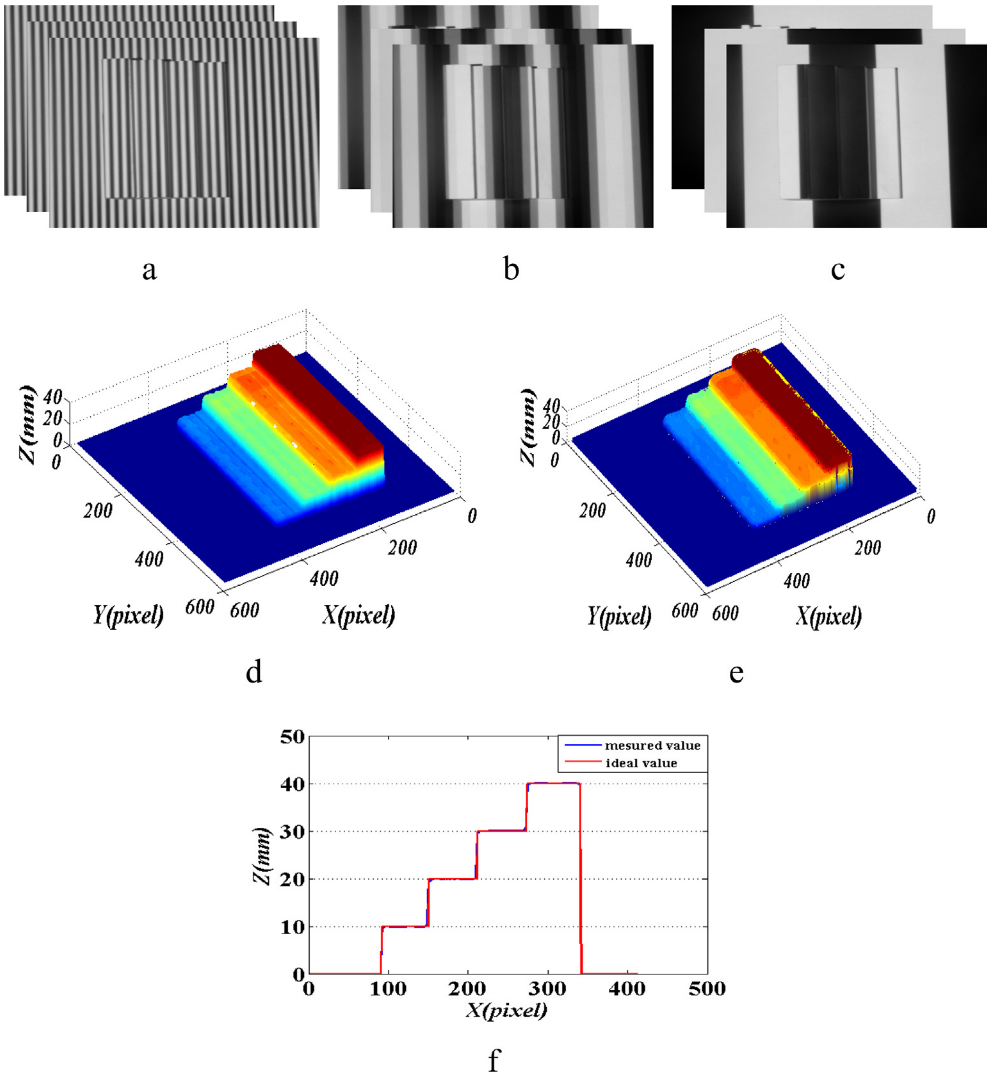

Fig. 8. 3D measurement of standard blocks: (a) sine fringe patterns, (b) phase encoding fringe patterns, (c) Gray code fringe patterns, (d) 3D measurement result of proposed method, (e) 3D measurement result of traditional phase method, (f) height distribution in the 110th row of the standard blocks.

Table 2
Experimental results for standard step block (mm).

Index	Real height	Measured height error	Absolute error	RMS
1	10.004	9.949	0.055	0.045
2	19.997	19.952	0.045	0.041
3	29.998	30.031	0.033	0.030
4	40.002	39.973	0.029	0.024

method, four standard blocks with different heights were measured. Fig. 8(a–c) show sine fringe patterns, phase-encoded fringe patterns and Gray code fringe patterns of the measured object, respectively. Fig. 8(d) shows the result is obtained by the S-shaped segmental phase encoding method proposed in this paper. Fig. 8(e) shows the result is obtained by the traditional phase encoding method (proposed by Wang). Fig. 8(f) shows the height distribution in the 110th row of the standard blocks, where the measured value is represented by a blue line and the ideal value is shown by a red line. The area of measurement was about 99 mm × 58 mm. The measurement errors of method proposed are shown in Table 2. From the table, we can see that the maximum absolute error was 0.055 mm and the maximum Root Mean Square (RMS) error was 0.045 mm. These measurement results prove the high accuracy of this method. After calculation and analysis, the accuracy of Wang's method is the maximum absolute error is 0.071 mm and the maximum RMS error is 0.056 mm.

4. Conclusions

In this paper, a 3D structured light measurement method based on S-shaped segmental phase encoding is presented. The method has three advantages. Firstly, Gray code is used to encode the phase encoding segment number, which can simplify the unwrapping algorithms. Furthermore, an S-shaped coding design is used to improve the accuracy of the order of the judgment fringe. Finally, the number of code words is expanded using the idea of segmentation to improve measurement accuracy. In summary, the proposed method can measure complex and isolated objects with high accuracy. The experimental results demonstrate the superiority of the proposed method in the measurement of complex objects and isolated objects.

Acknowledgments

This project is supported by the National Natural Science Foundation of China (Grant No. 61661034), Key research and development program of Jiangxi Province (Grant No. 20171BBE50012), Jiangxi Provincial Department of Education Science and Technology Program (Grant No. DA201808191), Foundation of Key Laboratory of

Nondestructive Testing(Nanchang Hangkong University), Ministry of Education (Grant No. EW201908087), Graduate Innovation Fund of Nanchang Hangkong University (Grant No. YC2018055).

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