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Comparison between ternary and binary Gray code-based phase unwrapping methods

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ABSTRACT

Phase-shifting profilometry using binary patterns with projector defocusing has been widely used for high-speed 3D measurement. Recently, a ternary Gray-code based phase unwrapping method has been proposed, which enables to accurately unwrap the phase but reduces the required binary patterns. This paper presents a comparison between the ternary and the traditional binary Gray code-based phase unwrapping methods.

Keywords: Phase-shifting profilometry, projector defocusing, phase unwrapping, ternary Gray code

1. INTRODUCTION

Phase-shifting profilometry (PSP) using binary patterns projection becomes increasingly important due to its high-speed and high-accuracy¹⁻⁴. The recent digital technologies make it possible for high-speed binary patterns projection (i.e., thousands frames per second)¹. When the projector is manually defocused, binary patterns become sinusoidal ones¹. By using a phase-shifting algorithm, the phase can be calculated from these sinusoidal patterns⁴. The calculated phase is wrapped in the range of $(-\pi, \pi]$, which contains 2π phase jumps⁵. A phase unwrapping is required to retrieve the absolute phase from the wrapped phase⁶. The traditional binary Gray code-based phase unwrapping method (i.e., G_C_2) is widely used because of its robustness, which requires $\lceil \log_2 f \rceil$ binary patterns to differentiate f fringe periods, where $\lceil \cdot \rceil$ is the ceiling function⁷. Recently, a ternary Gray code-based phase unwrapping method (i.e., G_C_3) has been proposed, by using a fewer number of $\lceil \log_3 f \rceil$ binary patterns⁸. In this paper, we present a comparison between the ternary and binary Gray code-based methods. The rest of the paper is organized as follows. Section 2 introduces the ternary Gray code-based phase unwrapping method. Section 3 provides the comparison. Section 4 concludes this paper.

2. TERNARY GRAY CODE-BASED PHASE UNWRAPPING METHOD

The ternary Gray code-based phase unwrapping method uses ternary (i.e., “0”, “1” and “2”) Gray code⁸. The used three states of “0”, “1” and “2” are denoted by black, gray and white patterns, respectively. By using a $(3, m)$ -Gray code mechanism, m binary patterns can generate 3^m code words for the phase unwrapping⁹. The gray pattern is created by using alternate black and white patterns (i.e., the narrowest squared binary pattern).

For clarity, two binary patterns including 9 fringe periods (i.e., $\overline{AB}, \overline{CD}, \overline{EF}, \dots, \overline{QR}$) are simulated and shown in Fig. 1. The fringe period is selected as $T = 20$ pixels. The two simulated binary patterns are denoted by B_1 and B_2 , respectively. Each binary pattern contains the same horizontal binary distribution, and binary distributions of the two binary patterns are shown in Fig. 2. In the distribution of B_1 , the 1st, 6th and 7th periods use the black pattern with the period of $T = 20$. The 3rd, 4th and 9th periods use the white pattern with the same period of $T = 20$. The 2nd, 5th and 8th periods use the narrowest squared binary patterns (i.e., alternate black and white), where the “0” and “1” states are assigned pixel by pixel along the horizontal direction. In the distribution of B_2 , the black, alternate black and white, and white patterns are assigned with the period of $3T$ successively.

Fig. 1 Two binary patterns.

Fig. 2 Two binary distributions.

The projector defocusing can be approximated by a 2D Gaussian filter, and the defocusing level can be described by the standard deviation σ ⁴. When the 2D Gaussian filter with a standard deviation $\sigma = 1.5$ is applied, both the two binary patterns are blurred and shown in Fig. 3, which are denoted by I_1^b and I_2^b , respectively. The two blurred patterns can be segmented into three states of “0”, “1” and “2” by⁸

$$S_k(x, y) = \begin{cases} 0, & \text{if } I_k^b(x, y) \leq Th_1, \\ 1, & \text{if } Th_1 < I_k^b(x, y) < Th_2, \\ 2, & \text{if } I_k^b(x, y) \geq Th_2. \end{cases} \quad (1)$$

where Th_1 and Th_2 denote two thresholds, and S_k denotes the segmented result of the k_{th} blurred pattern. The two thresholds can be simply selected as $Th_1 = 0.28$ and $Th_2 = 0.72$ ⁸. As shown in Fig. 3, the segmented patterns are denoted by S_1 and S_2 , respectively, whose values for 9 periods are provided in Table 1.

Based on the Gray-code $(3, m)$ mechanism⁸⁻⁹, we have

$$C(x, y) = \sum_{k=1}^m [S_k(x, y) \times 3^{k-1}], \quad (2)$$

where C denotes the decoded codeword, which is unique for each period. The fringe order K can be easily determined by referring to Table 1. Both the decoded codeword and the fringe order are also provided in Table 1. The absolute phase can be retrieved by⁸

$$\Phi(x, y) = \varphi(x, y) + K(x, y) \times 2\pi. \quad (3)$$

It is not difficult for readers to know Gray-code $(3, 3)$ and $(3, 4)$, which are more commonly used in real applications⁸. Generally, the fringe period is not selected too small to satisfy the discrete sampling rate, and also not selected too large to obtain a high-quality phase⁴. For commonly used fringe periods, such as $T = 18, 24, 30, \dots, 42$, etc., the above principle always works.

Fig. 3 Two blurred patterns and two segmented patterns.

Table 1. Gray-code (3,2).

S_1	0	1	2	2	1	0	0	1	2
S_2	0	0	0	1	1	1	2	2	2
C	0	1	2	5	4	3	6	7	8
K	0	1	2	3	4	5	6	7	8

3. COMPARISON

In the experiment, the fringe period is also selected as $T = 20$ pixels. A five-step phase-shifting algorithm is used, and thus five squared binary phase-shifting binary patterns are generated¹⁰. The developed system includes a TI DLP Discovery 4100 projector with a resolution of 1140×912 and a Basler CMOS acA2000 camera with a resolution of 800×600 . The fringe patterns include $f = 45.6$ (i.e., $912/20$) periods due to the projector's resolution. The G_C_2 and G_C_3 use $\lceil \log_2 45.6 \rceil = 6$ and $\lceil \log_3 45.6 \rceil = 4$ binary patterns, respectively. Therefore, the Gray-code (3,4) mechanism is used for the G_C_3 ⁸. A white flat board is placed in front of the projector with the distance of 75 cm and then measured.

The central 300×600 pixels of the captured patterns are analyzed. When the projector is manually defocused, the five squared binary patterns become sinusoidal, and two of them with a phase-shift of $2\pi/5$ are shown in Figs. 4(a)-4(b), respectively. Both the G_C_2 and G_C_3 used binary patterns are also blurred. The G_C_2 used 6 patterns are shown in Figs. 4(c)-4(h), respectively. The G_C_3 used 4 patterns are shown in Fig. 4(i)-4(l), respectively.

By using the five-step phase-shifting algorithm⁴, the wrapped phase is calculated and shown Fig. 5(a). One row of the calculated phase is shown in Fig. 6. Before doing the segmentation, all the captured blurred patterns should be normalized¹. The G_C_2 and G_C_3 are then applied, respectively. Their retrieved absolute phases are shown in Figs. 5(b) and 5(d), respectively. Because of the discrete sampling of the camera, both the two absolute phases contain unwrapping errors around 2π phase jumps pixels⁸. By using a simple median filtering¹⁰, this kind of error can be effectively removed. The filtered phases of the G_C_2 and G_C_3 become identical and correct. The final filtered phase is shown in Fig. 5(f).

By subtracting the retrieved absolute phases from the correct phase, unwrapping errors of the G_C_2 and G_C_3 are obtained and emphasized by black points in Figs. 5(c) and 5(e), respectively. The G_C_2 and G_C_3 generate 1001 and

2471 errors, respectively. The G_C_3 generate more errors than the G_C_2, because its segmentation sensitivity is higher than that of the G_C_2⁸. In Figs. 5(b)-5(d), two distributions at the same row are selected for the analysis. Their decoded codewords and their absolute phases are shown in Figs. 7-8, respectively. These unwrapping errors are around 2π phase jump pixels. This kind of error can be deemed as the impulsive noise, and the median filter can efficiently remove this impulsive noise¹⁰. When the median filtering is applied, both the G_C_2 and G_C_3 obtain the same correct phase as plotted by the black line in Fig. 8.

Fig. 4 The captured patterns: (a)-(b) two phase-shifting sinusoidal patterns, (c)-(h) the G_C_2 used 6 patterns, (i)-(l) the G_C_3 used 4 patterns.

Fig. 5 Experiment results: (a) the calculated wrapped phase, (b) the G_C_2 retrieved absolute phase, (c) unwrapping errors of the G_C_2, (d) the G_C_3 retrieved absolute phase, (e) unwrapping errors of the G_C_3, (f) the correct absolute phase after the median filtering is applied.

Fig. 6 One row of the calculated phase.

Fig. 7 The decoded codewords.

Fig. 8 The retrieved absolute phases.

For code pattern segmentation, the G_C_2 uses one threshold of 0.5^7 , and the G_C_3 needs two thresholds of $Th_1 = 1/4 + \tau/2$ and $Th_2 = 3/4 - \tau/2$, where τ denotes the segmentation range⁸. The number of unwrapping errors during increasing τ is shown in Fig. 9, which reduces first and then increases. In a large range of $[0, 0.1]$, the value of τ can be flexibly selected, and all the unwrapping errors can be removed by applying a median filtering¹⁰. The segmentation range is in inverse proportion to the defocusing level⁸. A large range of segmentation range allows the G_C_3 to be used for different defocusing levels.

Fig. 9 The number of unwrapping errors for different segmentation ranges.

4. CONCLUSION

This paper provides more details of the ternary Gray code-based phase unwrapping method and compares it with the traditional binary Gray code-based phase unwrapping method. It can be concluded that the ternary method can obviously reduce the required binary patterns without sacrificing the accuracy, which shows great potential when pursuing high-speed 3D measurement.

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