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3D measurement using combined Gray code and dual-frequency phase-shifting approach

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ABSTRACT

The combined Gray code and phase-shifting approach is a commonly used 3D measurement technique. In this technique, an error that equals integer multiples of the phase-shifted fringe period, i.e. period jump error, often exists in the absolute analog code, which can lead to gross measurement errors. To overcome this problem, the present paper proposes 3D measurement using a combined Gray code and dual-frequency phase-shifting approach. Based on 3D measurement using the combined Gray code and phase-shifting approach, one set of low-frequency phase-shifted fringe patterns with an odd-numbered multiple of the original phase-shifted fringe period is added. Thus, the absolute analog code measured value can be obtained by the combined Gray code and phase-shifting approach, and the low-frequency absolute analog code measured value can also be obtained by adding low-frequency phase-shifted fringe patterns. Then, the corrected absolute analog code measured value can be obtained by correcting the former by the latter, and the period jump errors can be eliminated, resulting in reliable analog code unwrapping. For the proposed approach, we established its measurement model, analyzed its measurement principle, expounded the mechanism of eliminating period jump errors by error analysis, and determined its applicable conditions. Theoretical analysis and experimental results show that the proposed approach can effectively eliminate period jump errors, reliably perform analog code unwrapping, and improve the measurement accuracy.

1. Introduction

As a non-contact active measurement approach, 3D measurement based on structured light has considerable potential for application in many fields, such as reverse engineering, medicine, and virtual reality [1–3]. The phase-shifting approach [4–6], which employs a digital fringe projection technique [7,8], has been widely adopted owing to its high measurement efficiency, sampling density, and accuracy. However, it can only obtain the wrapped phase with the principal value range $[0, 2\pi)$; it cannot reflect a 2π phase jump. Hence, it is necessary to obtain the absolute phase-by-phase unwrapping [9–12]. To gain a deeper understanding and facilitate analysis, in this paper, the wrapped phase and the absolute phase are multiplied by the same coefficient, and their results are defined as the wrapped analog code and absolute analog code, respectively. Obviously, the analog code and phase have the same physical meaning. The specific definitions are introduced in Section 2.1.

Accurate analog code unwrapping is a key technology and a challenging problem associated with the phase-shifting approach. At present, Gray code with high anti-interference ability [13] is commonly used for analog code unwrapping. The combined Gray code and phase-shifting approach allows measurement of discontinuous surfaces or surfaces with drastic height changes while providing high measurement accuracy [14–16]. However, non-uniform reflectivity of the measured surface, background light changes, non-ideal hardware performance, and noise can result in analog code decoding errors. The above-mentioned factors as well as the transition area in the conversion between black and white boundaries can result in errors in the Gray code value. These two types of errors can result in an error that equals integer multiples of the phase-shifted fringe period in the absolute analog code [17–19]. In this paper, these period errors are termed as 'period jump errors', which can result in gross errors in the measurement result.

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To reduce the period jump error in analog code unwrapping using Gray code, Zheng [20] proposed a self-correcting unwrapping approach that can determine the 2π phase jump position of the wrapped phase and the jump position of Gray code. Furthermore, period jump errors can be eliminated by Gray code correction on the basis of the position difference of two adjacent jump points. This approach does not project additional patterns, but its calculation process is complicated. Zhang [21] proposed an analog code unwrapping approach based on complementary Gray code. This approach projects an additional Gray code pattern that can obtain the two complementary decoding values. This analog code unwrapping using different Gray code values chosen by wrapped analog code can prevent period jump errors. Yu [22] proposed an unequal-period combined Gray code and phase-shifting approach. By projecting an additional Gray code pattern, the original Gray code will be subdivided and a Gray code value can be obtained. 'Compared with phase-shifted fringe patterns, Gray code patterns move several pixels to the left, and period jump errors can be prevented by analog code unwrapping through established mathematical equations. However, the above-mentioned approaches are limited to preventing only period jump errors of one fringe period near the Gray code jump point.

To eliminate the period jump errors more effectively, this paper proposes a combined Gray code and dual-frequency phase-shifting approach based on an analysis of the mechanism of the period jump error in the combined Gray code and phase-shifting approach. The proposed approach uses a set of additional low-frequency phase-shifted fringe patterns, and the low-frequency absolute analog code measured value can be obtained on the basis of the original absolute analog code measured value. Thus, the original value is corrected by the low-frequency absolute analog code measured value to eliminate period jump errors, and reliable unwrapped results can be obtained.

2. Combined Gray code and phase-shifting approach and its period jump error analysis

2.1. Principle of combined Gray code and phase-shifting approach

The principle of the combined Gray code and phase-shifting approach is to project phase-shifted fringe patterns of period T and Gray code patterns of period T sequentially. The j Gray code patterns divide the measurement space into 2^j subspaces [13], and each subspace corresponds to a unique Gray code value k_g, which is termed as the analog code order, $k_g \in \mathbf{N}$. Each subspace contains only one period of a phase-shifted fringe, and the subspace is theoretically infinitely subdivided by the wrapped phase φ' obtained by the phase-shifting approach [4]. The absolute phase $x' = 2\pi k_g + \varphi'$ can be obtained through phase unwrapping by the analog code order [19]. The above equation can be expressed as $(T/2\pi)x' = k_g T + (T/2\pi)\varphi'$. In this paper, wrapped analog code is defined as $\varphi = T\varphi'/(2\pi)$ with principal value range $[0, T)$, and absolute analog code is defined as $x = Tx'/(2\pi)$. Thus, x can be expressed as follows:

$$x = k_g T + \varphi. \tag{1}$$

The 3D surface shape of the measured object can be obtained from x on the basis of the triangulation method [15].

According to the above description, the truth value x_0 of the absolute analog code is the abscissa. The curves of k_g, φ, and x as well as their mutual position relationship are shown in Fig. 1.

2.2. Period jump error analysis of combined Gray code and phase-shifting approach

First, the mathematical model of the absolute analog code in the actual measurement is constructed. Eq. (1) is derived in the ideal case. However, in the actual measurement process, background light noise and device noise can produce errors Δk_g, $\Delta\varphi$, and Δx in the parameters k_g, φ, and x, respectively. Thus, the measured values of the analog code

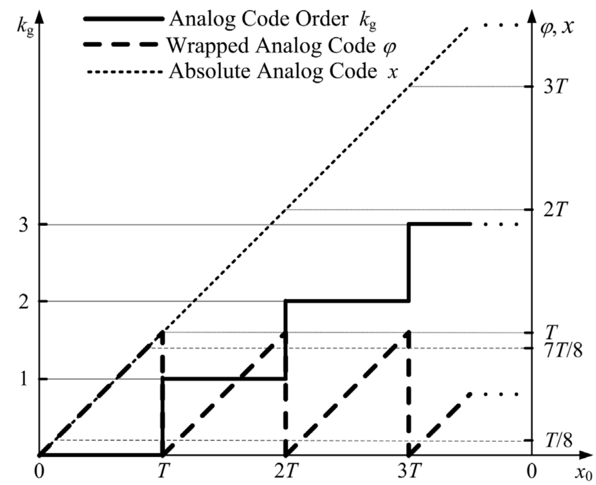

Fig. 1. Curves of k_g, φ, and x as well as their mutual position relationship.

Table 1
Period jump errors of combined Gray code and phase-shifting approach.

Subinterval	k	Δx
$\varphi \in [0, T/8)$	0	$\Delta k_g T + \Delta\varphi^c$
	1	$(\Delta k_g + 1)T + \Delta\varphi^c$
$\varphi \in [T/8, 7T/8)$	0	$\Delta k_g T + \Delta\varphi^c$
$\varphi \in [7T/8, T)$	0	$\Delta k_g T + \Delta\varphi^c$
	−1	$(\Delta k_g - 1)T + \Delta\varphi^c$

order, wrapped analog code, and absolute analog code are recorded as k_g^c, φ^c, and x^c, respectively, where $k_g^c = k_g + \Delta k_g$, $\varphi^c = \varphi + \Delta\varphi$, and $x^c = x + \Delta x$. Because $\varphi^c \in [0, T)$, $\Delta\varphi$ can be expressed by $\Delta\varphi = \Delta\varphi^c + kT$, where $k \in \{-1, 0, 1\}$, and $\Delta\varphi^c$ is termed as the residual analog code error. Then, from Eq. (1), we have

$$x^c = k_g^c T + \varphi^c = (k_g + \Delta k_g)T + kT + \Delta\varphi^c, \tag{2}$$

where the measured value k_g^c is obtained by decoding Gray code images, the measured value φ^c is obtained using phase-shifted fringe images by the phase-shifting approach, and the measured value x^c is obtained from Eq. (2), which can perform Gray code unwrapping. Eq. (2) is the measurement model of the combined Gray code and phase-shifting approach.

According to Eqs. (1) and (2), the absolute analog code measurement error Δx can be calculated as follows:

$$\Delta x = x^c - x = (\Delta k_g + k)T + \Delta\varphi^c = mT + \Delta\varphi^c, \tag{3}$$

where $m = \Delta k_m + k$, and the error Δx consists of two parts. The error $\Delta\varphi^c$ is produced by obtaining φ with the phase-shifting approach, and $|\Delta\varphi^c|$ is far smaller than T. When $m \neq 0$, the error mT is an integer multiple of T, $|mT|$ is far greater than $|\Delta\varphi^c|$, and mT is the period jump error. Obviously, period jump errors can lead to gross measurement errors, which limit the measurement accuracy significantly.

The analysis of period jump errors in the combined Gray code and phase-shifting approach is as follows. $|\Delta\varphi^c|$ is far smaller than T, and $\Delta\varphi^c$ is restricted as $|\Delta\varphi^c| < T/8$. Further, $|\Delta\varphi^c| < T/8$ is one of the applicable conditions of the approach proposed in Section 3.1, which will be discussed in Section 3.2. The period jump error analysis process and results of this approach are summarized in Table 1. The first column shows that the principal value range of φ is divided into three subintervals. As shown in the second column, the possible values of k can be determined according to $|\Delta\varphi^c| < T/8$. Finally, as shown in the third column, based on Eq. (3), the expression of Δx with Δk_g as its independent variable can be obtained by the value of k. Hence, the period jump error exists under three conditions: $k = 0$ and $\Delta k_g \neq 0$, $k = 1$ and $\Delta k_g \neq -1$, and $k = -1$ and $\Delta k_g \neq 1$.