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Unequal-period combination approach of gray code and phase-shifting for 3-D visual measurement

Shuang Yu [a,b], Jing Zhang [a], Xiaoyang Yu [b,*], Xiaoming Sun [b], Haibin Wu [b]

[a] College of Computer Science and Technology, Harbin Engineering University, Harbin 150001, China
[b] The Higher Educational Key Laboratory for Measuring & Control Technology and Instrumentations of Heilongjiang Province, Harbin University of Science and Technology, Harbin 150080, China

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ABSTRACT

Combination of Gray code and phase-shifting is the most practical and advanced approach for the structured light 3-D measurement so far, which is able to measure objects with complex and discontinuous surface. However, for the traditional combination of the Gray code and phase-shifting, the captured Gray code images are not always sharp cut-off in the black-white conversion boundaries, which may lead to wrong decoding analog code orders. Moreover, during the actual measurement, there also exists local decoding error for the wrapped analog code obtained with the phase-shifting approach. Therefore, for the traditional approach, the wrong analog code orders and the local decoding errors will consequently introduce the errors which are equivalent to a fringe period when the analog code is unwrapped. In order to avoid one-fringe period errors, we propose an approach which combines Gray code with phase-shifting according to unequal period. With theoretical analysis, we build the measurement model of the proposed approach, determine the applicable condition and optimize the Gray code encoding period and phase-shifting fringe period. The experimental results verify that the proposed approach can offer a reliable unwrapped analog code, which can be used in 3-D shape measurement.

1. Introduction

The visual 3-D measurement technologies [1] are a key developing direction in the 3-D measurement field. As an active visual 3-D measurement technique, the structured light approach is widely acknowledged with its practicality and development potential. Compared with the dot structured light and the line structured light, the encoded structured light [2,3] has become the developing tendency for the visual 3-D measurement due to its advantages of high efficiency, high speed and no need to scan.

The encoded structured light approach can be categorized into 3 types. The first type is the spatial-encoded structured light approach [4,5]. For this approach, we project patterns encoded in a certain way and then decode the captured images by comparing them with the related encoding patterns. The approach has a high measuring speed and is suitable for dynamic measurement, but it also has disadvantages of low sampling density, low anti-interference ability and low measurement accuracy. The second type is the direct-encoded structured light, of which every single encoded pixel is identified by the intensity or color of itself. This approach has the fastest measuring speed and the sampling density can reach up to pixel-level. However, due to the fact that the pixel-level codes are combined in one pattern, the used gray level scale or color spectrum is extremely wide, and consequently, the measurement accuracy is low. The last type is the time-encoded structured light. This approach projects various patterns with the time sequence and decodes by combining the related encoded pattern sequence. Compared with the other two methods, this approach has advantages of high sampling density and high measurement accuracy, but it also has a disadvantage of low measuring speed which is caused by using many encoded patterns.

The time-encoded structured light approach can also be divided into the digital time-encoded structured light [6,7], of which the pattern is encoded digitally, and the analog time-encoded structured light, of which the pattern is encoded with analog quantity. One widely used digital time-encoded approach is the Gray code binary fringe sequence [7]. With the Gray code, one binary code is only one bit different from its neighbor codes, which minimizes the chance of decoding mistakenly. This approach has a strong ability of anti-interference, but it also has a low measurement resolution for the sampling density is limited to a sub-space. For the analog time-encoded structured light approach, the phase-shifting technique (cosine phase-shifting [8–20], triangle phase-shifting [21–23] and trapezoid phase-shifting [24,25]) is one of the most used methods.

* Corresponding author.
E-mail address: yuxiaoyang@hrbust.edu.cn (X. Yu).

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For this approach, the cosine fringe patterns, the trapezoid fringe patterns or the triangle fringe patterns are projected to the surface of the measured object. Then, the fringe patterns distorted by the surface of the measured object are obtained to get the coordinates information. High sampling rate and high resolution are the advantages for the phase-shifting technique and the advantages come from the reason that analog codes are calculated point by point. However, if we use the fringe patterns that contain only one period of the analog code to cover the whole measuring space, the gray-scale space will have to be divided into pieces that are equal to the number of pixels in a row or in a column, which causes an extremely low ability of anti-interference. But if we use the fringe patterns with repetitive periods, namely, use the fringe patterns that contain n periods of the analog code to cover the whole measuring space, the anti-interference ability will increase. But the unwrapping algorithm may bring insurmountable analog code truncation problem, which makes it hard to measure the objects with drastic height changes or discontinuous surfaces. In order to apply the repetitive periods fringe patterns in the 3-D measurement, we have to use a proper analog code unwrapping algorithm to obtain the continual analog code distribution.

Recently, Combining the Gray code and the phase-shifting has become a developing trend and research hotspot for the structured light approach. Taking advantage of the good anti-interference ability of the Gray code, this type of approach unwrap the analog code with no error accumulation. Furthermore, it uses the phase-shifting technique to implement measurement, which is with high sampling density, high resolution and high measurement accuracy. With this type of approach, objects with drastic height changes or discontinuous surfaces can also be measured accurately. In the traditional Gray code-phase shifting combination approach, we obtain the wrapped analog code principal value with the phase-shifting technique, we unwrap the analog code according to the unique analog code order which are obtained by decoding Gray code. However, due to the disturbances caused by the non-uniform reflectivity of the measured object, the background intensity and the defocus, the captured Gray code fringe images are not always sharp cut-off in the black-white conversion boundaries, which will cause wrong results during the binarization process and consequently, lead to wrong analog code orders. Moreover, during the actual measuring process, the wave form of the captured fringe image is also not in accord with the ideal wave form because of the interferences like the noise, environment light, defocus and the nonlinear of the projector, etc. This will cause local decoding errors within the principal value range of analog code. Altogether, the wrong analog code orders and the local analog code errors will lead to sharp analog code jumps in the wrapped analog code, which are close to a fringe period [26–29]. We call them the 'period jump errors'. This period jump error will consequently lead to a huge measurement error in the measurement result, and in this paper, we name this measurement error as the 'gross error'. Although the researchers all over world have eliminated the period jump error to some degree with their methods [28], they also introduced the side effects such as a larger time expense, a lower automation and a bad universality, etc. Besides, for the measured object which has a complex shape, it is hard to eliminate the period jump error completely. An analog code unwrapping approach based on complementary Gray code [29] is able to provide a reliable unwrapped analog code distribution of the measured object with a very low probability of mistake. Compared with the traditional combination of the Gray code and phase-shifting, Zhang's approach [29] needs one extra Gray code pattern, and the code words number of Gray code is double of the traditional method. Furthermore, it usually needs a relatively complicated judging process when the analog code is unwrapped, but this approach eliminates the period jump error only by considering the wrong analog code order caused by the fact that the captured Gray code images are not always sharp cut-off in the black-white conversion boundaries. The application condition of this approach is not determined.

Therefore, in this paper, we analyze how the period jump error occurs in the traditional Gray code and phase-shifting combination approach and propose an unequal period combination approach of the Gray code and the phase-shifting, which, under certain premises, avoids the period jump error from the encoding principle. Besides, we optimize the Gray code encoding period and the phase-shifting fringe period. The exact analysis of the proposed approach will be given in the following chapter. Experimental results show that the proposed approach is able to provide a reliable unwrapped analog code distribution with an extremely low probability of mistake, even if the measured object has a complex or discontinuous surface. Compared with Zhang's approach, the proposed approach needs the same number of the Gray code patterns, but the proposed approach does not need the complicated judging formula during the analog code unwrapped process. In addition, the proposed approach avoids the period jump error taking both the wrong analog code order and local analog code error into consideration. Also, the application condition of the proposed approach is determined.

2. Equal-period combination approach of gray code and phase-shifting and the analysis of the period jump error

2.1. Equal-period combination approach

In the traditional equal-period combination approach of Gray code and phase-shifting, the Gray code encoding period and the phase-shifting fringe period are equal. Here in this paper, we call this approach the 'equal-period combination approach' [26–28,30–32]. In Fig. 1, the wave forms of the analog code order and the analog code principal value in the equal-period combination approach as well as their positional relationship are shown. Theoretically, the analog code order jump obtained by decoding the Gray code is in accord with the analog code principal value jump obtained by the phase-shifting technique. The Gray code encoding period and the phase-shifting fringe period are T pixels. Besides, φ

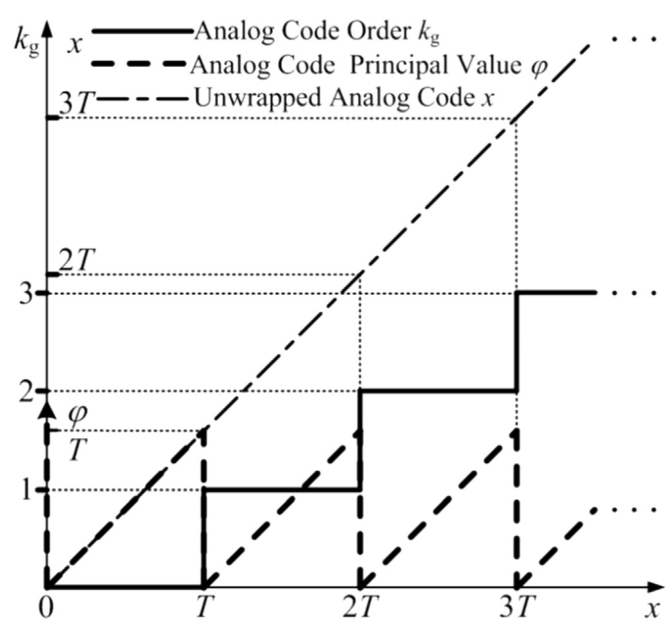

Fig. 1. The wave forms of the analog code order and the analog code principal value in the equal-period combination approach as well as their positional relationship.