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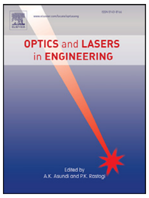

Flexible line-scan camera calibration method using a coded eight trigrams pattern

Kechen Song[a,b,*], Bin Hou[a,b], Menghui Niu[a,b], Xin Wen[a,b], Yunhui Yan[a,b]

[a] *School of Mechanical Engineering & Automation, Northeastern University, Shenyang, Liaoning, China*
[b] *Key Laboratory of Vibration and Control of Aero-Propulsion Systems Ministry of Education of China, Northeastern University, Shenyang, Liaoning, China*

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ABSTRACT

This paper presents a novel, simple, yet flexible line-scan camera calibration method using a coded eight trigrams pattern. A new target pattern with orientation coded information is firstly proposed, which has a circular symmetry structure to expand the validity of the calibration range and obtain more effective coded information from various directions. Moreover, the proposed pattern is more easily positioned and detected in image when a rectangular stripes pattern is used as a calculation base. Besides, the proposed method does not require other auxiliary equipment during the calibration process due to the calibration target is convenient to carry. The applicability and accuracy of the proposed calibration method are verified by the simulation and real experiments.

1. Introduction

The dynamic three-dimensional (3D) shape measurement is an important technology in industrial instrumentation and measurement research fields. In the past few years, the structured light measurement methods using matrix camera have been rapidly developed [1], such as phase measuring profilometry (PMP) [2,3], and Fourier transformation profilometry (FTP) [4,5]. In order to measure some large-scale industrial objects with high resolution and high speed, stereo line-scan cameras were employed to reconstruct 3D shape [6–8].

Camera calibration plays a key role in the 3D shape measurement, which will directly affect the results of 3D reconstruction. To achieve high accuracy, a large number of camera calibration methods have been proposed, such as two planes [9–11], planar checkerboard [12], spherical [13–16], and other planar targets [17–19]. However, the above methods are mainly used to calibrate the matrix camera and cannot be directly used for line-scan camera owing to the sensor structure of one-dimensional line image.

In order to realize the calibration of line-scan camera, some researchers moved the line-scan camera with a constant velocity (i.e., scanning calibration) to obtain the two-dimensional image, such as Draréni et al. [20] and Hui et al. [21,22]. However, the cameras are not allowed to be moved in many actual industrial measurement conditions, i.e., these scanning calibration methods are not available in some industrial environments. To make up for this shortcoming, an auxiliary matrix camera was often employed [23–25]. But the extra camera increases the complexity of the calibration method.

In view of the actual requirements of industrial measurement, the static calibration method was firstly introduced by Horaud et al. [26] using the principle of cross-ratio invariance and several feature lines. This method mainly used the intersection points of the camera's viewing plane and the feature lines to calibrate the camera. Although the method is very simple to operate, the result of calibration is greatly affected by the precision of the displacements. In order to solve this demerit, Luna et al. [27] and Li et al. [28] proposed different 3D calibration patterns to calibrate the line-scan camera. Both of these methods used multiple planes to calculate the parameters avoid the position variance of the pattern and thus more flexible. However, these simple and limited line patterns cannot provide enough more projective information in the obtained image. To overcome this limitation, Lilienblum et al. [29,30] proposed the coded pattern using more straight lines and obtained impressive results. Since the coded pattern employed too many straight lines, this method increases the complexity and manufacturing cost of the calibration target.

In this paper, a novel, simple, yet flexible line-scan camera calibration method using a coded eight trigrams pattern is proposed. Firstly, a new target pattern with orientation coded information is proposed, which evolved from the ancient map. Since the circular symmetry structure of the target, the validity of the calibration range is expanded and the effective coded information can be obtained from various directions when the camera viewing plane intersects with it. Secondly, the calculation process becomes simple since the pattern is more easily positioned

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[*] Corresponding author at: Key Laboratory of Vibration and Control of Aero-Propulsion Systems Ministry of Education of China, Northeastern University, Shenyang, Liaoning, China

E-mail addresses: songkc@me.neu.edu.cn (K. Song), yanyh@mail.neu.edu.cn (Y. Yan).

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and detected in image when a rectangular stripes pattern is used as a calculation base. Moreover, since the calibration method uses a mobilizable target which is convenient to carry, it does not require other auxiliary equipment during the calibration process, i.e., the operability of the calibration is improved under the industrial field.

The rest of this paper is organized as follows: The origin of the idea and the specific design scheme are described in Section 2. The theoretical model used in the calibration process is introduced in Section 3. The specific calculation process of the calibration method is demonstrated in Section 4. The experimental verification and analysis of calibration methods are clarified in Section 5, including computer simulation experiments and real calibration experiments. The overall calibration work is summarized in Section 6.

2. The proposed calibration target

The design of the pure straight lines target pattern makes the calibration pattern single and repeat, and lacks mutual connection between the lines. In addition, the characteristic information on the target in the camera's viewing field cannot directly reveal the location characteristics of the target. Moreover, the difficulty of detection is increased due to the graphical construction of the lines. If some position information between the target and the camera can be fed back according to the direct information of the image, it is convenient to manually adjust the target to obtain an effective image in an appropriate position in the calibration process. In view of the above analysis, a new pattern with azimuthal coded information is applied to the target design. The design process of the proposed calibration target includes the following two parts: the evolutionary process of the proposed coded eight trigrams pattern and the design of the proposed calibration target.

2.1. The evolutionary process of the proposed coded eight trigrams pattern

There is a simple and beautiful pattern in Chinese traditional culture. A common circle curve is divided into an end to end two "fish", surrounded marked with the symbol called "the Eight Trigrams", which is known Taiji and eight trigrams pattern. In the Yi-ology, the eight trigrams pattern is divided into "up, middle, down" three Yao (in the traditional Yi-ology it called "Nature, Earth and Human"), which represent the three elements in the system.

The basic unit of eight trigrams pattern is "Yao". The "Yao" is also the basic unit to describe the essential factors attributes of system. If the attribute of element is negative then it is "Yin Yao", with the symbol "--" represents; if the attribute of element is positive then it is "Yang Yao", with the symbol "—" represents.

To encode the Yin and Yang attributes of Yao, Yin Yao is represented by 0, Yang Yao is represented by 1. The coded results as shown in Fig. 1(a). In this work, in order to simplify the eight trigrams pattern, black stripe is used to represent the Yin Yao, white stripe is used to represent the Yang Yao, as shown in Fig. 1(b). Since the octagon calculation is more complex and is not good for the detection of the following feature line, so it is converted into a circle to make up for the above shortcomings, as shown in Fig. 1(c). From Fig. 1(c), it can be seen that the order of decimal numbers is chaotic, i.e., it is not completely clockwise or counterclockwise. For the convenience of subsequent coded, the order of decimal numbers is adjusted in a counterclockwise order, as shown in Fig. 1(d).

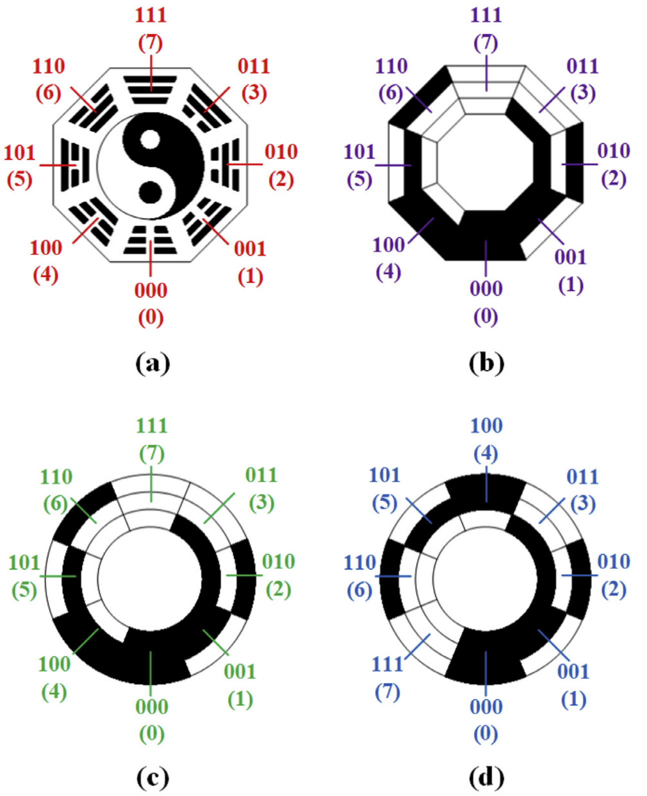

Fig. 1. The evolutionary process of the proposed coded eight trigrams pattern.

2.2. The design of the proposed calibration target

In the field of machine vision, line-scan camera is a special type owing to its sensor has only one line of light-sensitive elements compared to the matrix camera. Hence, the viewing field of the line-scan camera in width is narrow. According to the Section 2.1, the designed circle contains eight coded messages, so each code has a smaller range. However, in the same viewing field, the coded information of eight trigrams pattern is easily confused compared to the few codes pattern, as shown in Fig. 2. Fig. 2(c) is a partial magnification of Fig. 2(a) in the viewing field. From Fig. 2(c), it can be seen that there are at least six different viewing lines (i.e., Case 1, Case 2, …, Case 6) under the viewing field. In this situation, the number of the intersection points cannot be uniquely identified. Therefore, the coordinates of the intersection points cannot be accurately calculated. In order to overcome the shortcoming, the designed circle can only use two coded messages, as shown in Fig. 2(b).

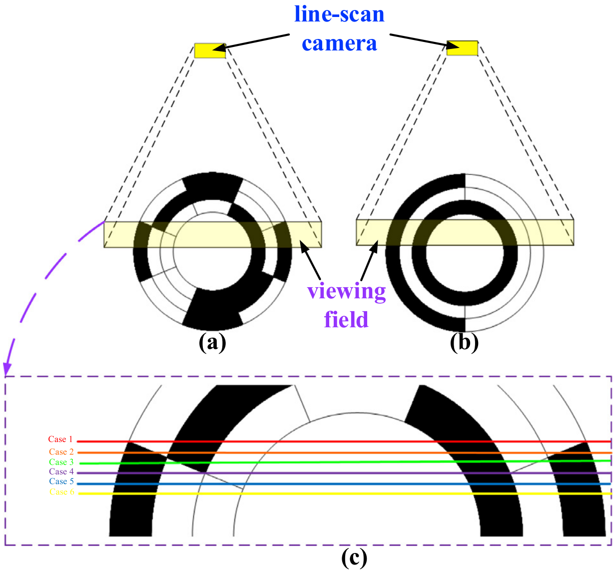

Fig. 2. The viewing fild of eight codes and two codes.

In order to build a complete calibration target, four different coded circles and several vertical straight lines are combined to make up a