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Original Citation

Xu, Yongjia, Gao, Feng, Zhang, Zonghua and Jiang, Xiang (2017) A calibration method for non-overlapping cameras based on mirrored phase target. In: The 13th International Symposium on Measurement Technology and Intelligent Instruments, 22-25 September 2017, Xi'an, Shaanxi, China. (Unpublished)

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A calibration method for non-overlapping cameras based on mirrored phase target

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Keywords: Camera calibration; Non-overlapping cameras, Phase target

Abstract. A novel calibration method for non-overlapping cameras is proposed in this paper. A LCD screen is used as a phase target to display two groups of orthogonal phase-shifted sinusoidal patterns during the calibration process. Through a mirror reflection, the phase target is captured by the cameras respectively. The relations between each camera and the phase target can be obtained according the proposed algorithm. Then the relation between the cameras can be calculated by treating the phase target as an intermediate value. The proposed method is more flexible than conventional mirror-based approach, because it do not require the common identification points and is robust to out-of-focus images. Both simulation work and experimental results show the proposed calibration method has a good result in calibrating a non-overlapping cameras system.

Introduction

Multiple cameras are applied in visual measurement [1, 2], scene surveillance [3, 4], and mobile robotics [5, 6] in case of single camera could not satisfy the functional requirement. Due to the design restrictions and cost savings, the field of view (FOV) of the cameras are unable to be guaranteed overlapped. In these cases, the camera parameter and the relative positions of the cameras should be calibrated for a system consisted of non-overlapping cameras.

Recently, several types of calibration approaches are researched to calibrate the non-overlapping cameras. One type of the approaches introduces extra calibration tools to assist the calibration process. Pagel et al. [5] developed an approach for calibrating non-overlapping cameras with hand-eye calibration (HEC) technique. Guan et al. [7] researched an approach to obtain the internal and external parameters of non-overlapping camera fig based on HEC. Lamprecht et al. [8] calibrated a non-overlapping cameras system on a vehicle online. However these approaches are sensitive to the localization accuracy of the calibration tools and are failure when the cameras are unable to move. Other approaches were researched based on a target which moves in the cameras' FOV. Ali et al. [9] proposed an approach for simultaneously recovering the trajectory of a target and the external calibration parameters of non-overlapping cameras. However this type of approaches cannot meet the accuracy demand of visual measurement. Researchers studied to extend the target size to cover the FOV of cameras simultaneously. Liu et al. [10] proposed an approach to calibrate the extrinsic parameters of multiple vision sensors based on 1D target. Dong et al. [11] combined a multiple cameras system using arbitrarily distributed encoded targets on a wall. However this type of approaches is limited by the target size and cannot calibrate cameras with 180 degree angle. The mirror-based calibration approaches [12, 13] applied a planar mirror to generate an overlapping view between cameras and calibrate cameras based on a 2D calibration target. This type of approaches improves the flexibility in the design of calibration target size, avoids the error introduced by positioning tools and does not require the cameras' movement during calibration process. However it is less convenient to implement because cameras have to find the same identification points though the mirror reflection. Moreover, the common points cannot be extracted successfully when the target is not in the depth of field (DOF) of the cameras.

This paper presents a novel calibration method based on mirrored phase target for non-overlapping cameras. Though the mirror reflection, the relation between each camera and the phase target can be obtained. Then the relation between the cameras can be calculated by treating the phase target as an intermediate value. Since the phase target is consisted of sinusoidal fringe patterns, the proposed method is robust to out-of-focus.

Principle

The illustration of the proposed method is illustrated in Fig. 1. A LCD screen is used to display two groups of orthogonal phase-shifting sinusoidal patterns. Through the reflection of flat mirrors, the patterns are captured by the cameras. After phase-shifting and phase unwrapped algorithm [13] applied, two orthogonal absolute phase maps can be obtained. The calculated phase maps are used as targets during the calibration process.

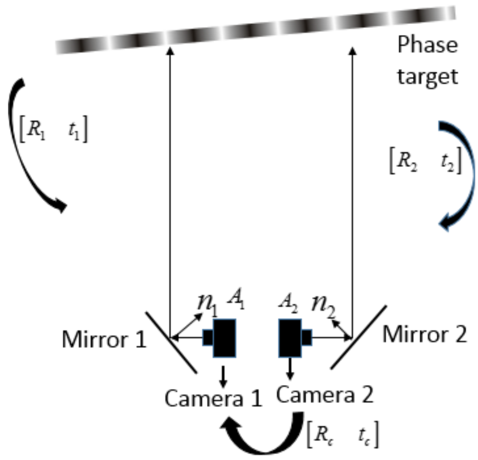

Fig. 1. The illustration of the proposed method

For a pixel m of camera 1, the corresponding physical position $M'(x_w, y_w)$ in the mirrored LCD coordinate system can be uniquely located based on its absolute phase value (φ_x, φ_y) according to Eq. (1).

$$\begin{cases} x_w = (n_p \cdot p / 2\pi) \cdot \varphi_x \\ y_w = (n_p \cdot p / 2\pi) \cdot \varphi_y \end{cases}. \tag{1}$$

where p is the size of LCD pixel pitch and n_p is the number of LCD pixels per fringe period. Camera parameter A_1 and the relation $[R' \quad t']$ between mirrored screen and the camera coordinate system can be obtained based on the pinhole model by moving mirror 1 to at least 3 arbitrary positions:

$$sm = A_1 \cdot [R' \quad t'] \cdot M'. \tag{2}$$

The relation $[R_1 \quad t_1]$ between the camera and the real screen can be calculated with the least-squares solution by at least three mirror reflections according to Eq. (3).

$$\begin{cases} R' = (I - 2nn^T)R_1 \\ t' = (I - 2nn^T)t_1 + 2dn \end{cases}. \tag{3}$$

where n is the mirror normal vector expressed in camera frame, d is the distance between the mirror and the camera center. n can be obtained based on Eq. (4).

$$\begin{cases} n_i = (m_{ik} \times m_{ij}) / \left\| m_{ik} \times m_{ij} \right\| \\ n_j = (m_{ji} \times m_{jk}) / \left\| m_{ji} \times m_{jk} \right\| \\ n_k = (m_{ik} \times m_{jk}) / \left\| m_{ik} \times m_{jk} \right\| \end{cases} . \tag{4}$$

where i, j, k represent three arbitrary mirror positions. m is the unit vector that is perpendicular to both two mirror normal vectors, and can be calculated according to Eq. (5).

$$\begin{cases} (R_i^{'} - R_j^{'})^T \cdot m_{ij} = 0 \\ (R_j^{'} - R_k^{'})^T \cdot m_{jk} = 0 \\ (R_i^{'} - R_k^{'})^T \cdot m_{ik} = 0 \end{cases} . \tag{5}$$

The remaining unknown parameter d in Eq. (3) can be solved by a linear equations as

$$\begin{bmatrix} (I - n_i n_i^T) & 2n_i & 0 & 0 \\ (I - n_j n_j^T) & 0 & 2n_j & 0 \\ (I - n_3 n_3^T) & 0 & 0 & 2n_k \end{bmatrix} \begin{bmatrix} t_1 \\ d_i \\ d_j \\ d_k \end{bmatrix} = \begin{bmatrix} t_i^{'} \\ t_j^{'} \\ t_k^{'} \end{bmatrix} . \tag{6}$$

where I is a 3x3 identity matrix. Until now, the initial value of the camera parameter, relation between camera 1 and the LCD are obtained, and then they are optimized by minimizing the following function with Levenberg-Marquardt Algorithm:

$$\sum_{i=1}^{g} \sum_{j=1}^{k} \left\| m_{ij} - \hat{m}(A_1, R_{1i}, t_{1i}, n_i, d_i, M_{ij}) \right\| . \tag{7}$$

where M is the corresponding point of m in terms of the LCD, g is the number of mirror movement, k is the number of camera pixels. Based on the same algorithm, the parameter A_2 of camera 2 and the relation $[R_2 \quad t_2]$ between camera 2 and the LCD can be calculated. Then the relation $[R_c \quad t_c]$ between cameras can be determined according to Eq. (8) by treating the LCD as an intermediate value.

$$\begin{cases} R_c = R_2 \cdot R_1^{-1} \\ t_c = t_2^{-1} - R_2 \cdot R_1^{-1} \cdot t_1^{-1} \end{cases} . \tag{8}$$

The whole calibration workflow is shown in Fig.2.

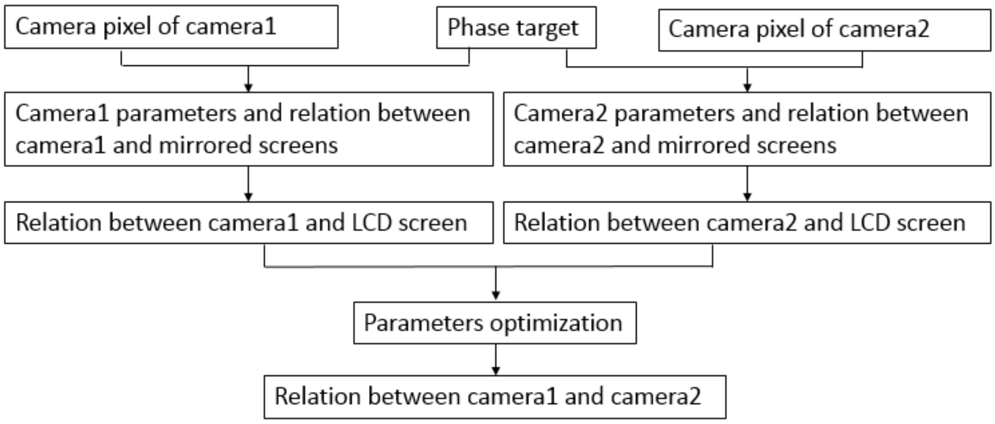

Fig. 2. Workflow of the proposed method

Experiment and results

Simulation study

To test the proposed calibration method, a system with two non-overlapping cameras is simulated as shown in Fig. 3.

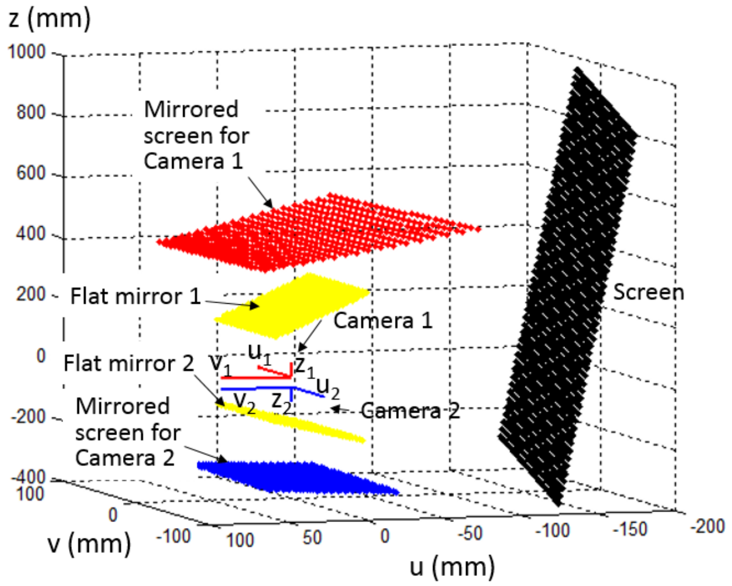

Fig. 3. The simulation setup.

The size of the simulated camera image is 1280×960 with the principal point at (640,480) pixel. The euler angles between the two camera systems are 0^0, 0^0, 180^0 in terms of α , β and γ respectively. During the calibration process, a screen is used as the phase target to calibrate the system parameters. The phase target is captured by the two cameras through the reflection of two flat mirrors. In order to simulate the real experimental environment, random noise with a maximum value of 0.005 mm is added to the obtained physical positions. Arbitrary moving the flat mirror to more than three positions, the mirrored screens can be located at different calibration positions in terms of the cameras. The calibration result is shown in table 1.

Table 1. Calibration result with simulated data

Relative poses	Euler angles			Relative translation		
	$\alpha[^\circ]$	$\beta[^\circ]$	$\gamma[^\circ]$	$t_x[mm]$	$t_y[mm]$	$t_z[mm]$
Ture value	0	0	180	0	0	35
Calibration result	-0.0069	0.0024	179.9987	-0.0054	-0.1922	35.1161
Residual	0.0069	0.0024	0.0013	0.0054	0.1922	0.1161

Experimental study and discussion

An experiment has been conducted on a non-overlapping cameras system. The setup hardware system is illustrated in Fig. 4. The LCD monitor is Dell E151Fpp with a resolution of 1280×1024. The pixel pitch of the LCD is 0.297 mm. The camera is Lumenera CCD sensor (Model Lw235M) with a resolution of 1616×1216. The camera lens is a Navitar lens with 35 mm fixed focal length. The cameras are mounted with an approximate angle of 180^0. In fact, it is difficult to obtain the real relation between the two camera coordinate systems. In order to compare with the calibration result from the proposed method, the relation between the camera coordinate systems is estimated by ignoring the deviation between the camera coordinate center and the CCD geometric center in terms of the x-y plane. The translations between the two coordinate systems along with u and v direction are estimated to be both 0. The euler angles between the two camera systems are estimated to be 0^0, 0^0,

180^0 in terms of α, β and γ respectively. Because the translation along z direction is impossible to be estimated, this value is not be compared. The calibration result is shown in Table 2.

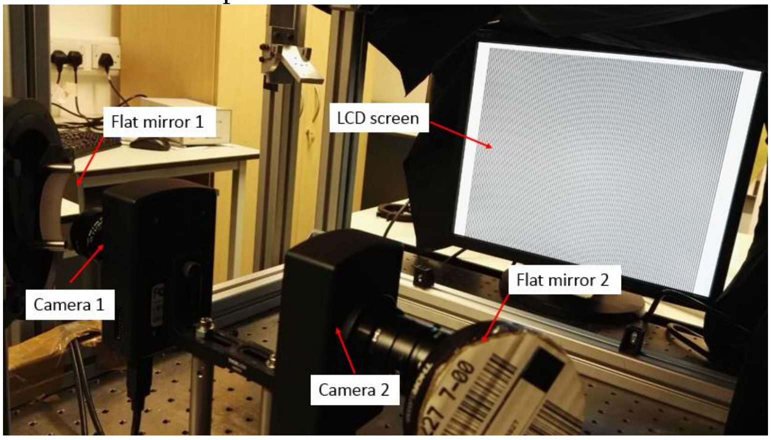

Fig. 4. The experiment setup.

Table 2. Calibration result with experimental data

Relative poses	Euler angles			Relative translation	
	$\alpha[^\circ]$	$\beta[^\circ]$	$\gamma[^\circ]$	$t_x[mm]$	$t_y[mm]$
Estimated value	0	0	180	0	0
Calibration result	-0.9851	-0.8834	-179.5616	-4.9478	6.2277

Conclusion

A calibration method based on mirrored phase target is proposed to calibrate the system with non-overlapping cameras. The simulation study shows the proposed calibration method is effective and accurate to obtain the relation between two non-overlapping cameras. An experiment study is also conducted to test the proposed method. The difference between the estimated and the calibration result can be seen the deviation between the camera coordinate center and the CCD geometric center. Further studies will be made on increasing the calibration speed.

Acknowledgment

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding (Grant Ref: EP/P006930/1, EP/I033424/1 and EP/K018345/1) and the European Horizon 2020 through Marie Sklodowska-Curie Individual Fellowship Scheme (NO: 707466-3DRM).

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