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Structured light system calibration with unidirectional fringe patterns

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ABSTRACT

For the calibration of a structured light system, one type of highly accurate calibration method was developed by treating the projector as an inverse camera. This type of method typically creates pixel-to-pixel mapping between a camera point and a projector point using fringe patterns and resultant phase maps in orthogonal directions. However, requiring orthogonal patterns limits its feasibility of implementation on systems where the illumination device (e.g. grating projectors, interferometers, etc.) only supports fringe projection in one direction. This paper introduces a novel calibration method that only uses patterns in a single direction. We have theoretically proved that there exists one degree-of-freedom of redundancy in conventional calibration methods, making it possible to reduce the requirement of using orthogonal fringe patterns. Experiments show that under a measurement range of 200 mm(X)× 150 mm (Y) × 120 mm (Z), our measurement results are comparable to the results obtained using conventional calibration method. Evaluated by repeatedly measuring a sphere with 147.726 mm diameter, our measurement accuracy on average can be as high as 0.20 mm with a standard deviation of 0.12 mm.

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1. Introduction

Optical means of three-dimensional (3D) surface measurement has been of great importance in a variety of applications ranging from industrial inspection, robotics, and other applications. Among all optical 3D surface measurement techniques, the structured light technology has been increasingly studied owing to its merits of flexible system setup, high-speed and high-resolution measurements [1,2]. The measurement accuracy of structured light technology is largely determined by whether one could achieve highly accurate system calibration, which requires accurately calibrating both the image acquisition device (e.g. camera) and the active illumination device (e.g. projector).

The calibration of a camera has been well studied over the past several decades. Initial calibration techniques started from developing techniques with precisely manufactured 3D calibration targets [3,4]. Then, Tsai [5] reduced the calibration target to two-dimensional (2D) ones with out-of-plane rigid shift employed to provide depth information. Later, as a milestone in camera calibration, Zhang [6] has enabled calibration with 2D targets that can be flexibly arranged with arbitrary orientations. Following Zhang's method, researchers developed advanced technologies that allow the usage of imperfect [7–10] or active targets [11–13]. Some recent advances even extended such technology to out-of-focus camera calibration [14].

For a structured light system, the projector should also be calibrated to realize absolute 3D reconstruction. Yet, such task is comparatively more complicated since unlike a camera, the projector cannot capture images by itself. Methods that extract the exact system parameters (e.g. positions, orientations) of the camera and projector [15–17] provide a solution, yet such methods typically require a time-consuming calibration process. Because of the level of complexity of projector calibration, the reference-plane-based calibration [18–21] is still a prevailing technology in the field of optics. Such methods have the merit of a easy-to-compute phase-to-depth conversion. However, this kind of technology requires the reference plane to have a good optical property and surface flatness, and the accuracy of calibration could be affected if the imaging lens is non-telecentric. To address the limitations of a simple reference-plane-based calibration, optimization techniques (e.g. polynomial fitting) [22–26] were used to decode depth information from projector patterns' codifications (e.g. phase value).

Apart from the aforementioned technologies, a different set of technologies were developed which were originated from the concept of treating the projector as an inverse camera [27]. Zhang and Huang [28] developed the enabling technology which allows the projector to "capture" images like a camera. The technology essentially maps a camera point to a projector point using absolute phase, in which both horizontal and vertical patterns are required to locate both u and v in 2D projector pixel coordinate. With such mapping scheme, the target images for the projector can also be created and thus the projector can be calibrated using similar strategies as used in camera calibration. Following Zhang and Huang's work, there were a series of different technologies to improve the accuracy including linear interpolation [29],

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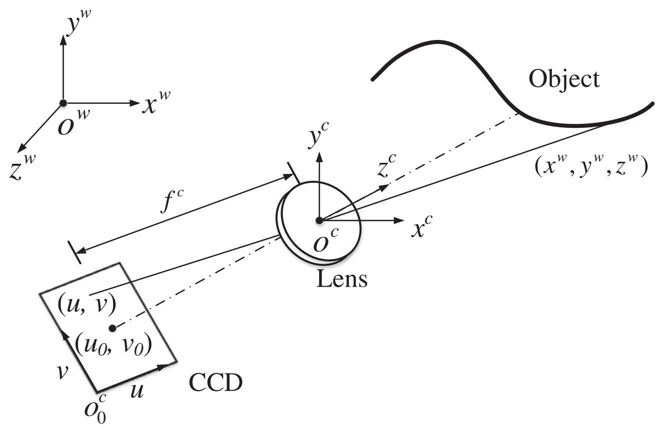

Fig. 1. Pinhole imaging model. The picture is reprinted from [33].

bundle adjustment [30], residual error compensation [31], or enhanced feature detection [32]. Further innovations have extended the calibration to a system with an out-of-focus projector [33] and to a large-range measurement system [34]. Such type of methods successfully addressed the long existing puzzle for projector calibration. However, a crucial limitation of this technology is its requirement of patterns in orthogonal directions. This technology has been proven very efficient for a structured light system with digital fringe projection. Since a video projector is programmable by the user, one can easily generate patterns in orthogonal directions. Yet for other types of systems with different fringe generation schemes (e.g. grating diffractions, interference, etc.), it is challenging to produce patterns in orthogonal directions, making such types of calibration methods difficult to be implemented.

In this research, we introduce a novel calibration method for the structured light system requiring only unidirectional patterns. We mathematically proved that for 3D reconstruction, not all parameters in the projector's projection matrix are required to be known. Therefore, there exists one degree-of-freedom (DOF) of redundancy in the conventional Zhang and Huang's calibration method [28], which makes patterns in orthogonal directions over-constrained for system calibration. Our method takes one DOF away from projector calibration with an innovated least-square estimation method, where patterns with only one direction are sufficient to support calibration and 3D coordinate computation. Experiments demonstrate that our proposed calibration framework can achieve 3D shape measurement results comparable to the conventional Zhang and Huang's calibration method. Particularly, we achieved an average accuracy of 0.20 mm with a standard deviation of 0.12 mm evaluated by repeatedly measuring a spherical object with $d = 147.726$ mm.

Section 2 introduces the related theoretical background as well as our proposed least-square projector partial calibration method. Section 3 will demonstrate the experimental results to show the success of our method. Section 4 will summarize the contributions of this research.

2. Principles

In this section, we first introduce the related theoretical foundations such as the basics of pinhole imaging model, phase shifting technique and camera calibration. Then, we will introduce our proposed unidirectional projector's least-square partial calibration method and the associated computation of 3D reconstruction.

2.1. Pinhole imaging model

In a structured light system, both the camera and fringe projector respect a well-known pinhole imaging model as shown in Fig. 1. The associated mathematical formulation is described in Eq. (1)

$$s\begin{bmatrix}u\\v\\1\end{bmatrix}=\begin{bmatrix}f_u&\gamma&u_0\\0&f_v&v_0\\0&0&1\end{bmatrix}\begin{bmatrix}r_{11}&r_{12}&r_{13}&t_1\\r_{21}&r_{22}&r_{23}&t_2\\r_{31}&r_{32}&r_{33}&t_3\end{bmatrix}\begin{bmatrix}x^w\\y^w\\z^w\\1\end{bmatrix}. \tag{1}$$

In this model, s denotes the scaling factor. r_{ij} and t_i are respectively the rotation and translation parameters which transform a point (x^w, y^w, z^w) in the world coordinate system to a point (x^c, y^c, z^c) in the camera lens coordinate system. f_u, f_v, γ, (u_0, v_0) are all intrinsic parameters of the imaging lens, where f_u, f_v are the effective focal lengths along u and v directions, γ is the skew factor of u and v axes, and (u_0, v_0) is the principal point on 2D pixel coordinate. To further simplify the model, one can perform matrix multiplication to obtain a combined projection matrix M.

$$\mathbf{M}=\begin{bmatrix}f_u&\gamma&u_0\\0&f_v&v_0\\0&0&1\end{bmatrix}\begin{bmatrix}r_{11}&r_{12}&r_{13}&t_1\\r_{21}&r_{22}&r_{23}&t_2\\r_{31}&r_{32}&r_{33}&t_3\end{bmatrix}, \tag{2}$$

$$=\begin{bmatrix}m_{11}&m_{12}&m_{13}&m_{14}\\m_{21}&m_{22}&m_{23}&m_{24}\\m_{31}&m_{32}&m_{33}&m_{34}\end{bmatrix}, \tag{3}$$

The simplified model for the camera and the projector can be expressed using the following equations, where superscript ^{c} and ^{p} denote the camera and the projector, respectively.

$$s^c\begin{bmatrix}u^c\\v^c\\1\end{bmatrix}=\begin{bmatrix}m^c_{11}&m^c_{12}&m^c_{13}&m^c_{14}\\m^c_{21}&m^c_{22}&m^c_{23}&m^c_{24}\\m^c_{31}&m^c_{32}&m^c_{33}&m^c_{34}\end{bmatrix}\begin{bmatrix}x^w\\y^w\\z^w\\1\end{bmatrix}, \tag{4}$$

$$s^p\begin{bmatrix}u^p\\v^p\\1\end{bmatrix}=\begin{bmatrix}m^p_{11}&m^p_{12}&m^p_{13}&m^p_{14}\\m^p_{21}&m^p_{22}&m^p_{23}&m^p_{24}\\m^p_{31}&m^p_{32}&m^p_{33}&m^p_{34}\end{bmatrix}\begin{bmatrix}x^w\\y^w\\z^w\\1\end{bmatrix}, \tag{5}$$

2.2. Camera calibration and target 3D estimation

The camera calibration has been well established during the past several decades. In this research, we adopted the well-known Zhang's calibration method [6] and the camera calibration software toolbox provided by OpenCV. The layout of our calibration target is shown in Fig. 2(a), on which the circle centers serve as feature points. Essentially, the camera calibration is composed of two parts: intrinsic and extrinsic calibrations.

The camera intrinsic calibration basically estimates the intrinsic parameters $(f_u, f_v, \gamma, u_0, v_0)$. We use the camera to take images of different target poses (an example is shown in Fig. 2(b)). On each captured target pose, we extract the feature points (e.g. circle centers) for iterative optimization of intrinsic parameters' estimation provided by OpenCV camera calibration toolbox. After intrinsic calibration, we obtained the intrinsic matrix of the camera as

$$\begin{bmatrix}f^c_u&\gamma^c&u^c_0\\0&f^c_v&v^c_0\\0&0&1\end{bmatrix}=\begin{bmatrix}2081.481&0&602.996\\0&2087.706&533.027\\0&0&1\end{bmatrix}. \tag{6}$$

In this research, we coincide the world coordinate with the camera lens coordinate (i.e. $x^c = x^w$, $y^c = y^w$, $z^c = z^w$):

$$\begin{bmatrix}r^c_{11}&r^c_{12}&r^c_{13}&t^c_1\\r^c_{21}&r^c_{22}&r^c_{23}&t^c_2\\r^c_{31}&r^c_{32}&r^c_{33}&t^c_3\end{bmatrix}=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\end{bmatrix}. \tag{7}$$

Then, after matrix multiplication, the final projection matrix is obtained by

$$\begin{bmatrix}m^c_{11}&m^c_{12}&m^c_{13}&m^c_{14}\\m^c_{21}&m^c_{22}&m^c_{23}&m^c_{24}\\m^c_{31}&m^c_{32}&m^c_{33}&m^c_{34}\end{bmatrix}=\begin{bmatrix}2081.481&0&602.996&0\\0&2087.706&533.027&0\\0&0&1&0\end{bmatrix}. \tag{8}$$

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