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Calibration method for a structured light measurement system with two different focal length cameras

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ABSTRACT

During reconstructing objects with complex shapes, 3D object surfaces are anticipated with an elaborate description to surface features and a fast acquiring speed. While a Camera–Projector Structured Light (CPSL) system with a constant focal length cannot achieve the two goals. The CPSL system with a Long Focal Length (LFL) camera has a high resolution and a small measurement area, therefore, high sampling density and low measurement efficiency. Conversely, the system with a Short Focal Length (SFL) camera has high measuring efficiency without enough sampling density. To accomplish the two goals, we propose a novel system integrating with two types of CPSL system. One system with the SFL camera fast obtains the overall morphology of objects. Another with the LFL camera acquires the details of surface features very well. To integrate them, a novel calibration method is presented. Experimental results verify the robustness and accuracy of the proposed calibration method.

1. Introduction

Generally, existing optical 3D measurement techniques can be broadly divided into passive and active methods [1,2]. Among active measuring techniques, the structured light system is well studied for its outstanding features like fast speed, high accuracy and non-contact measurement [3,4]. An accurate calibration of intrinsic and extrinsic parameters is crucial for the structured light system [5]. There are several methods presented in literatures, which are based on different techniques, such as Neural Networks [6,7], Bundle Adjustment [8–13], or Absolute Phase [14]. The calibration process varies depending on the available system parameter information and the system setup. Besides, Zhang and Huang [15] proposed a novel method that enabled a projector to "capture" images like a camera. Li and Shi [16] improved this method, which replaced the chess grids with a circular array, and got better results. Liao and Cai [17] calibrated the camera firstly and then used the calibration result to calibrate the projector, while no corresponding information was described to the presented calibration method. Chen and Xi [18] used a 2D flat board with evenly distributed circular marks, so the 3D lattice of reference points lay in one common world coordinate system. But it needed an accurate moving mechanism. Luo et al. [19] proposed a calibration method without projector calibration, in which the projector's line-of-sights served as spatially vectors in variant to the environment. Four reference planes were introduced and a look-up-table was built for the camera–projector pixel correspondence. Wei et al. [20] proposed to merely estimate equations of two light stripe planes, and derived other

Abbreviations: CPSL, Camera–Projector Structured Light; SFL, Short Focal Length; LFL, Long Focal Length.

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planes accordingly. But the method is only suitable for structured light system with line patterns and there is error propagation as the 3D coordinates of the control points depends on camera parameters. Sansoni et al. [21] focused on three parameters: distance between the projector and the video-camera, called baseline, the distance of the baseline from the reference surface, and the orientation of the projector with respect to the video-camera. But it was difficult to implement the system by restricting on the pattern direction and the parallelism between the baseline and the reference plane.

Now days, there are some 3D reconstruction systems based on the structured light measurement principle, such as a structure of two cameras with a projector [22] or a structure of one camera with a projector [16]. But these systems have just one constant focal length. During the process of acquiring point clouds of object surfaces, we hope the acquiring process has a fast speed and a clear expression to some complex structures (such as full of surface textures) on the object surface. But it is difficult to obtain two targets by the structured light system with a constant focal length camera.

In order to obtain two targets, a novel structured light system with two different focal length cameras is proposed as shown in Fig. 1. This system contains two systems: one with the SFL camera and another with the LFL camera. Fig. 2 illustrates that the system with the SFL camera cannot clearly acquire the details of object surfaces. The 3D reconstruction process can be divided into three steps: firstly, the overall morphology of an object is obtained by the structured light system with the SFL camera. And then, some important details of the object surface are captured by the structured light system with the LFL camera. Finally, two kinds of point clouds are merged. The structured light system with two resolutions not only improves the measurement efficiency, but also obtains the good description to the details of surface feature.

The rest of this paper is organized as follows. Section 2 describes the principle of our calibration method. In Section 3, we go into the details of the proposed calibration process. Section 4 presents experimental results

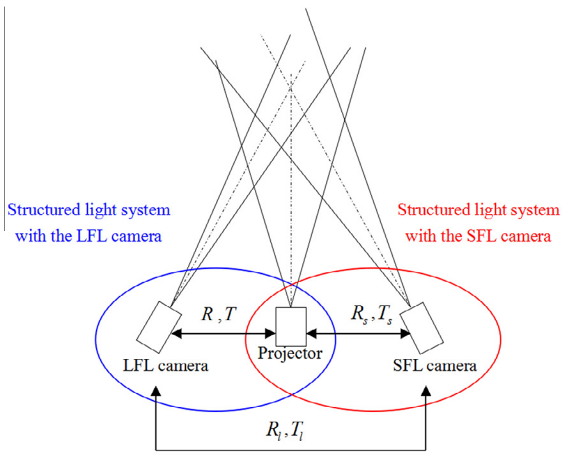

Fig. 1. Sketch map of the proposed structured light system.

demonstrating the quality of our system. Finally, we conclude in Section 5.

2. Calibration principle of our proposed system

The extrinsic calibration process of the structured light system with the LFL camera is significantly simplified by our proposed calibration method. In Fig. 1, $R_s(3 \times 3)$ and $T_s(3 \times 1)$ are the rotation matrix and translation matrix between the projector and the SFL camera. R_l and T_l denote the relationship of the SFL camera and the LFL camera, R and T the relationship of the LFL camera and projector. $X_p = (x_p, y_p, z_p)^T$, $X_s = (x_s, y_s, z_s)^T$ and $X_l = (x_l, y_l, z_l)^T$ are the 3D coordinates of point M in the projector coordinate system, the SFL camera coordinate system and the LFL camera coordinate system, respectively. The relationship between X_p, X_s and X_l can be expressed as follows:

$$X_p = R_s X_s + T_s, \tag{1}$$

$$X_s = R_l X_l + T_l. \tag{2}$$

The rotation matrix R and translation matrix T between the LFL camera and projector can be easily calculated from Eqs. (1) and (2):

$$X_p = R X_l + T, \tag{3}$$

where

$$R = R_s R_l, \tag{4}$$

$$T = R_s T_l + T_s. \tag{5}$$

In Fig. 1, the calibration process of our proposed system has three steps: (1) Calibrating the LFL camera and the structured light system with the SFL camera; (2) Calculating R_l and T_l between the SFL camera and LFL camera; (3) Calculating extrinsic parameters (R,T) of the structured light system with the LFL camera.

3. System calibration

3.1. The calibration method of the structured light system with the SFL camera

In this study, the calibration method of the structured light system with the SFL camera follows Li's method [16]. The differences between Li's and our method lie in two aspects: one is that a gamma pre-correction method [23] is used to reduce phase errors caused by the gamma distortion, instead of the LUT method in Li's method [24]. Another is that Gray code and phase-shifting method [25] is used to unwrap the absolute phase, while Li utilized multi-frequency heterodyne principle in his research [26].

3.1.1. Intrinsic parameters calibration of the structured light system with the SFL camera

In order to simplify the calibration process of the structured light system with one camera, the projector is treated as a camera. By doing this, the corresponding calibration process is equivalent to calibrate a traditional stereo vision system. Because the projector could not capture the image of the calibration board directly, a Gray