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A self-recalibration method based on scale-invariant registration for structured light measurement systems

Rui Chen [a,b], Jing Xu [a,*], Song Zhang [c], Heping Chen [d], Yong Guan [b], Ken Chen [a]

[a] State Key Laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing, 100084 China
[b] Beijing Advanced Innovation Center for Imaging Technology, Capital Normal University, Beijing, 100048 China
[c] School of Mechanical Engineering, Purdue University, West Lafayette, IN, 47907 USA
[d] Ingram School of Engineering, Texas State University, San Marcos, TX, 78746 USA

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ABSTRACT

The accuracy of structured light measurement depends on delicate offline calibration. However, in some practical applications, the system is supposed to be reconfigured so frequently to track the target that an online calibration is required. To this end, this paper proposes a rapid and autonomous self-recalibration method. For the proposed method, first, the rotation matrix and the normalized translation vector are attained from the fundamental matrix; second, the scale factor is acquired based on scale-invariant registration such that the actual translation vector is obtained. Experiments have been conducted to verify the effectiveness of our proposed method and the results indicate a high degree of accuracy.

1. Introduction

The use of optical measurement techniques has increased in different areas in recent years. Compared with other methods, such as stereo vision [1], laser scanning [2], shape from motion [3], and the time of light [4] method, the structured light method has the advantages of low cost, small amounts of calculation, fast measurement speed, and high spatial resolution [5–8]. Thus, it is widely applied in many fields, such as workpiece inspection, motion tracking, and reverse engineering.

The structured light measurement system is composed of a projector and a camera. During the measurement, a set of encoded patterns is shot to the object by the projector, and the deformed patterns are captured and decoded by the camera. Finally, the 3D shape can be calculated using triangulation. The prerequisite of measurement is calibrating the intrinsic and extrinsic parameters of the camera and the projector. For most existing calibration methods for structured light measurement systems, an accurate calibration gauge or movement equipment is required; also, the relative position and the orientation between the camera and the projector are supposed to be fixed [9,10].

However, in practical applications such as robot navigation, extrinsic parameters are desired to maximize the field of view (FOV), leading to continuous tracking of the measurement target. This action is similar to the phenomenon of two human eyes autonomously adjusting to view an object at different distances. Because the extrinsic parameters of the system change during the measurement procedure, the recalibration of extrinsic parameters needs to be performed online. Thus, the traditional offline calibration method based on a calibration gauge cannot be directly applied to this type of calibration.

Self-recalibration is a solution to the above problems and has been widely studied recently. For the self-recalibration method, the intrinsic parameters of the system are often assumed to be known and constant, and only the extrinsic parameters are needed to be recalibrated. In Ref. [11], the extrinsic parameters are calculated using the corresponding point coordinates, and the solutions obtained by using different numbers of points are discussed. However, these corresponding points have to be non-planar, moreover, the scale factor is uncalibrated such that it cannot be used for accurate 3D reconstruction. In Ref. [12], a planar surface is used to obtain the relative position and the orientation, where the plane constraint is used during the calculation. In the above methods, the translation vector between the projector and the camera is considered as a normalized vector, and the scale factor is missing. Therefore, the size of the measurement target cannot be determined by the recalibration result. Moreover, a special calibration plane is also needed. In Ref. [13], the actual relative position and the orientation can be attained, but the measurement system has only two degrees of freedom (DOFs); that is, the projector can move only along the y-axis and rotate around the z-axis.

* Corresponding author.
E-mail address: jingxu@tsinghua.edu.cn (J. Xu).

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In Ref. [14], the extrinsic parameters are attained by measuring the object from two different positions and searching for point correspondence based on the texture of the object. This leads to large computational costs and ambiguities. In Ref. [15], multiple cameras are used for a surplus measurement value, leading to increased installation complexity.

There is a strong demand for an online self-recalibration method to autonomously and rapidly calibrate the extrinsic parameters without any extra calibration gauge, especially the translation vector. To this end, this paper proposes a self-recalibration method for the structured light measurement system based on scale-invariant registration. For the proposed method, first, the rotation matrix and the normalized translation vector are attained through the encoded pattern projection. Second, the scale factor is calibrated by registering the two point clouds of the same object with the scale-invariant registration method. Finally, the actual size of the object can be determined by using the proposed calibration method. The rest of the paper is organized as follows: the mathematic model of the measurement system is described in Section 2. The calibration of the rotation matrix and the normalized translation vector is described in Section 3. The scale factor acquisition is described in Section 4. The entire recalibration process, experiments, and results are shown in Section 5. In Section 6, our work is concluded.

2. Mathematic models of camera and projector

The structured light measurement system is composed of a projector and a camera. In this paper, a pinhole model is used for both the camera and the projector, where the projector is considered as a pseudo-camera. The world coordinate system is coincident with the projector coordinate system, and the rotation matrix and the translation vector from camera to projector are R and t respectively as shown in Fig. 1.

For a 3D point P, its corresponding image pixel coordinates in the camera and the projector m_c, m_p can be attained by:

$$m_c = \alpha K_c P_c m_p = \beta K_p P_p \tag{1}$$

where $P_p = P$, $P_c = RP_p + t$, $m_c = [u_c, v_c, 1]^T$,

$$m_p = [u_p, v_p, 1]^T, \quad K_c = \begin{bmatrix} k_{xc} & 0 & o_{xc} \\ 0 & k_{yc} & o_{yc} \\ 0 & 0 & 1 \end{bmatrix}, \quad K_p = \begin{bmatrix} k_{xp} & 0 & o_{xp} \\ 0 & k_{yp} & o_{yp} \\ 0 & 0 & 1 \end{bmatrix}$$

are the intrinsic parameter matrices of the camera and the projector, and α, β are non-zero scale coefficients.

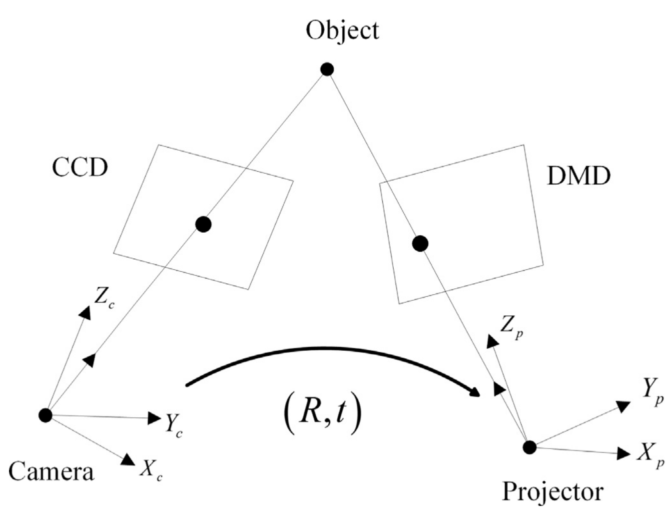

Fig. 1. Geometrical relations of the structured light measurement system.

Moreover, because of the lens distortion of the camera or the projector, the actual image pixel coordinates may derivate from the ideal ones, which can be expressed as [15]:

$$\begin{aligned} u' &= \left(1 + a_0 r^2 + a_1 r^4 + a_2 r^6\right)u + s_0 r^2 + \left(p_0 + p_2 r^2\right)\left(r^2 + 2u^2\right) \\ v' &= \left(1 + a_0 r^2 + a_1 r^4 + a_2 r^6\right)v + s_1 r^2 + \left(p_1 + p_3 r^2\right)\left(r^2 + 2v^2\right) \\ r^2 &= u^2 + v^2 \end{aligned} \tag{2}$$

where u, v are the ideal image pixel coordinates of the camera or the projector, u', v' are the actual image pixel coordinates, and $\{a_i\}$, $\{s_i\}$, $\{p_i\}$ are the lens distortion coefficients of the camera or the projector.

According to Eqs. (1) and (2), when K_c, K_p, $\{a_i^c\}$, $\{s_i^c\}$, $\{p_i^c\}$, $\{a_i^p\}$, $\{s_i^p\}$, $\{p_i^p\}$, R, t are known, the world 3D coordinate P can be calculated from m_c and m_p . Because intrinsic parameters K_c, K_p, $\{a_i^c\}$, $\{s_i^c\}$, $\{p_i^c\}$, $\{a_i^p\}$, $\{s_i^p\}$, $\{p_i^p\}$ are determined by the lens and the CCD of the camera and the DMD of the projector, which are constant for one specific camera or projector, whereas extrinsic parameters R, t are determined by the relative position and the orientation between the camera and the projector, the calibration process of the structured light system is composed of two procedures.

The intrinsic parameters need to be calibrated only once for camera and projector. This is known as the static calibration procedure. The extrinsic parameters need to be recalibrated as many times as the position and the orientation between the camera and the projector change. This is known as the dynamic recalibration procedure. The dynamic recalibration of extrinsic parameters is expected to be performed online rapidly and autonomously; that is, self-recalibration of extrinsic parameters is the important task of the structured light measurement system with varied extrinsic parameters. Thus, we focus on the extrinsic parameter self-recalibration in this paper.

3. Rotation matrix and normalized translation vector calibration

The position and the orientation between the camera and the projector are contained in the fundamental matrix, which constrain the camera and projector pixel coordinates corresponding to a common physical 3D point. To recalibrate the extrinsic parameters, we first obtain the fundamental matrix through encoded pattern projection. Second, the rotation matrix and the normalized translation vector between the camera and the projector are further decomposed from the fundamental matrix.

3.1. Fundamental matrix calculation

The relation between the object point coordinate P_c in camera coordinate frame and P_p in projector coordinate frame can be expressed as:

$$P_c = RP_p + t \tag{3}$$

yielding to

$$P_c - t = RP_p \tag{4}$$

And because the cross production of two vectors is perpendicular to both vectors, the following equation could be obtained:

$$\left(P_c - t\right)^T \left(t \times P_c\right) = 0 \tag{5}$$

Combining Eqs. (3) and (4), the constraint between P_c and P_p can be obtained as: