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# Accurate 3D measurement system and calibration for speckle projection method

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ABSTRACT

Triangulation with structured light projection is a well-established deformation measurement technique, which is utilized extensively in many fields. But all the existing calibration methods need to consider the influence of lens distortion and perspective error, which is indispensable with the use of conventional lens. In order to minimize such disadvantages, the telecentric lens is a good choice. Based on speckle projection, a system for deformation measurement is developed with the telecentric lens. Correspondingly, an effective calibration method is presented in detail. Experiments are performed to validate the availability and reliability of the calibration method. Results are compared with ESPI and good agreement is found between them. The system can also be used to measure the dynamic deformation and then results are also given.



## 1. Introduction

Triangulation with structured light projection is a well-established deformation measurement technique. Compared with interferometric methods such as holography [1–8], moiré [9–12] and electronic speckle pattern interferometry (ESPI) [13–18], this technique demands simple optical arrangement and does not need vibration isolation. Hence, it has been utilized extensively in many fields. Fringe projection [19–23] and speckle projection [24] are the two main types of structured light projection.

A typical triangulation with structured light projection consists of a projector and a camera. The projector is used to project a certain pattern onto the object surface. Due to the height modulation of the object surface, the projected pattern is distorted and captured by the camera, which is placed at an angle to the projection direction. Then surface profile or deformation of object can be reconstructed with the aid of digital image processing technique. In fringe projection, the Fourier transform method [21] and the phase-shifting technique [19,20] are frequently employed. The 2D digital image correlation method [24] is often adopted for speckle projection.

The key to an accurate reconstruction of object surface and deformation measurement is the proper calibration of each element used in the structured light projection system. Many calibration approaches have been presented. Tsai [25] described a versatile calibration technique in which radial lens distortion was considered. Radial lens distortion was also modeled in a flexible technique developed by Zhang [26]. Weng et al. [27] proposed a camera model that accounted for major sources of camera distortion, namely, radial, decentering, and thin prism distortions. Based on structured light projection, a novel systematic calibration was proposed by Zhang and Huang [28], in which the projector was enabled to “capture” images like a camera, thus making the calibration of a projector the same as that of a camera. Therefore, the calibration of structured light systems became essentially the same as the calibration of traditional stereovision systems, which is well established. Recently, Chen et al. [29] proposed an accurate and systematic calibration method to improve the measurement accuracy of camera–projector system and could improve the accuracy by 47%. And in his calibration model, higher to fourth order radial and tangential lens distortion were considered. another calibration method is also available in Ref. [30]. In a word, with the use of conventional lens, all the above-mentioned calibrations take into account the influence of lens distortion, which is the intrinsic characteristic of conventional lens. And there are many other circumstances in which lens distortion is not considered, which is not advisable. In addition, conventional lenses exhibit varying magnification for objects at different distances from the lens (perspective error). Telecentric lenses can minimize lens distortion (in the range of 0.1%) and provide constant magnification as the distance from the lens changes (within depth of field, DOF). Consequently, the lens distortion can be neglected, which will make calibration rather simple.

In this paper, we develop an accurate 3D measurement and calibration system by use of telecentric lens, based on speckle projection of structured light projection. This paper is organized

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as follows. The principle of such measurement system is described and is compared with that of the conventional setup in Section 2. The calibration procedure is described in detail in Section 3. In Section 4, the performance of the calibration is shown on experimental measurements, then the results are compared to ESPI results, and good agreement is found between the two methods, which demonstrates the system's availability and reliability. Finally, conclusions are presented in Section 5.

## 2. Principle of the method

### 2.1. Conventional setup

Fig. 1 shows the conventional schematic diagram of speckle projection method. A CCD camera and a projector are set at the same plane, which is parallel to the reference plane (undeformed state of object surface). The $z$ axis is the normal direction of the reference plane. Point $P$ is the center of the exit pupil for the projector and point $I$ is the center of the entrance pupil for the CCD camera. Point $O$ is the intersection of the optical axes of the projector and the CCD camera. The projector is used to project artificial random speckle to the reference plane. After deformation, the object is changed to surface from plane ($h(x,y)$: deformation). Two images are captured before and after deformation, respectively. The speckle originally projected to point A of the reference plane is now projected to point C of surface, and then reflected along ray CI to the CCD camera. Point B on the reference plane is the prolongation end of ray IC.

As $\Delta BCA \sim \Delta ICP$, $\Delta x$ and deformation $h(x,y)$ have the following relationship:

$$\frac{\Delta x}{L} = \frac{h(x,y)}{H-h(x,y)} \tag{1}$$

When $H \gg h(x,y)$, the corresponding size of image (in pixel) of $\Delta x$ is

$$\Delta_i = M\,\Delta x = \frac{MLh}{H} \tag{2}$$

where $M$ is the constant magnification factor (unit: pixel/μm) in the reference plane.

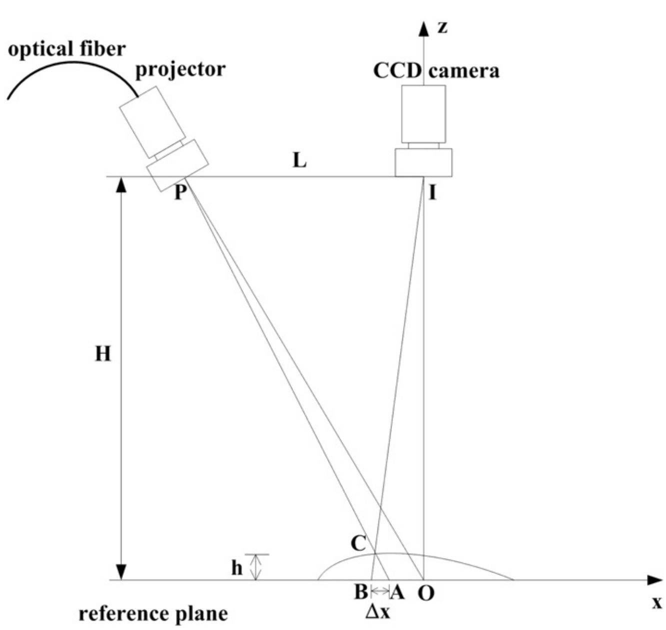


**Fig. 1.** Conventional schematic diagram of speckle projection method.

Therefore, the calibration coefficient is

$$k = \frac{h}{\Delta_i} = \frac{H}{ML} \tag{3}$$

Equation (3) shows that coefficient $k$ is a constant dependent only on the experimental setup. After calibration, $k$ will be obtained.

With the digital image correlation method applied to these two images, the offset $\Delta_i$ in the images will be figured out and the deformation will be acquired by the equation $h{=}k\Delta_i$.

### 2.2. Telecentric setup

Object-space (or object-side) telecentric lens creates images of the same size for objects at any distance (within DOF) and has constant angle of view across the entire field of view (FOV). Fig. 2 is an optical path of basic principles behind telecentric lenses. An aperture stop is placed at the rear principal focus of the lens. The chief rays (oblique rays which pass through the center of the aperture stop, highlighted in blue in Fig. 2) are parallel to the optical axis in front of the lens. An object that is too close or too far from the lens may still be out of focus, but the resulting blurry image will be the same size as the correctly focused image would be, as the centroid of the image remains the same throughout the different object distances. In addition, object-space telecentric lens minimizes lens distortion and provides higher image resolution. So it is used in this setup.

Fig. 3 is the telecentric schematic diagram of speckle projection method. A 0.5 × telecentric lens is used as camera lens with FOV 12.8 mm, DOF ± 2.1 mm at F10 and telecentricity less than 0.1°. Object is imaged to a CCD camera (Basler, scA1600-14fm) with a resolution of 1628 × 1236 pixels. One conventional lens is used for the projector to project speckle to object surface.

In Fig. 3, $L_2$ is the FOV of the telecentric lens; $PO_1$ and $O_1I$ are the optical axes of two lens, respectively. As mentioned above, the ray BC is parallel to optical axis $O_1I$ of CCD camera, which means that speckle originally projected to point A of the reference plane is now projected to point C of surface, and reflected along ray BC to CCD camera.

Similar to the analysis in Section 2.1, the following is obtained:

$$\Delta_i = M\,\Delta x = M\left(\frac{h}{\tan\alpha} + \frac{h}{\tan\beta}\right)$$

in which $\tan\beta = H/(L_1+x)$, $M$ is the constant magnification factor in the reference plane for the telecentric lens. Therefore,

$$\Delta_i = Mh\left(\frac{1}{\tan\alpha} + \frac{L_1+x}{H}\right) = (ax+b)h \tag{4}$$

where

$$a = \frac{M}{H}, \quad b = M\left(\frac{1}{\tan\alpha} + \frac{L_1}{H}\right)$$

$$k = \frac{h}{\Delta_i} = \frac{1}{ax+b} \tag{5}$$

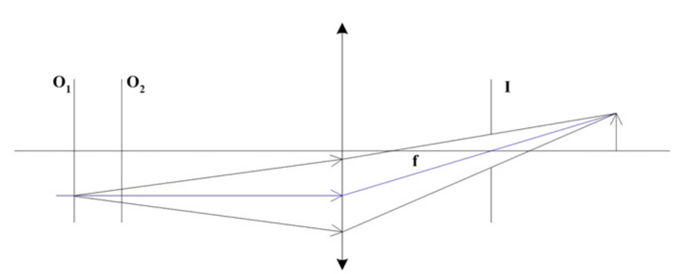


**Fig. 2.** Optical path of basic principles behind telecentric lenses.