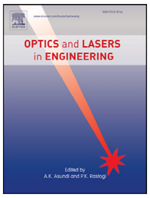
Optics and Lasers in Engineering 107 (2018) 21–27

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Low-speed-camera-array-based high-speed three-dimensional deformation measurement method: Principle, validation, and application

Ran Chen[a], Zhongwei Li[a], Kai Zhong[a,*], Xingjian Liu[a], Yuh Jin Chao[b], Yusheng Shi[a]

[a] *State Key Laboratory of Material Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan, China*
[b] *Department of Mechanical Engineering, University of South Carolina, Columbia, SC 29208, USA*

ARTICLE INFO

Keywords:
Low-speed camera array
High-speed three-dimensional deformation measurement
Calibration

ABSTRACT

High-resolution imaging devices are of interest in the development of accurate 3D vision systems. However, it is challenging to achieve a balance between the image capturing speed and resolution. The image capturing speed is relatively low for high-resolution imaging devices, which restricts their applications in high-speed 3D measurements. Therefore, a low-speed-camera-array imaging method for high-speed 3D deformation measurements is proposed. Compared with existing methods using high-speed imaging devices, it has the advantages of low cost and high flexibility achieved by combining low-speed cameras into a stereo camera array high-speed imaging system. In order to achieve accurate 3D measurements, a bundle-adjustment-principle-based system calibration method is proposed. Four experiments, including an accuracy experiment, repeatability experiment, vibration measurement of a plastic board, and out-of-plane displacement measurement of rotating blades, demonstrated the accuracy and effectiveness of the proposed method.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Stereo vision systems are widely used in observation, measurement, and analysis of the three-dimensional (3D) shape, displacement, and deformation of high-speed dynamic objects [1–5]. In these systems, high-speed cameras have to be used to record the fast movement or deformation of the measured objects. Most high-speed cameras capture images at a relatively lower resolution owing to the limitations of transfer bandwidth and storage space. However, for a 3D vision system, a higher image resolution is preferred to achieve more accurate 3D measurements.

In the development of high-speed 3D measurement systems, significant research effort has been devoted to the development of single-camera stereovision to reduce hardware investment [6–13]. Among the single-camera stereovision techniques, the simplest and most commonly used approaches were realized by placing an additional optical device in front of the existing imaging lens [6–12]. Using such additional optical devices, two views of the measured object's surface with different optical paths can be simultaneously imaged onto the left and right halves of the camera sensor; however, this leads to a substantial reduction in spatial resolution. In order to utilize the full spatial resolution of the camera, Yu [13] proposed a color stereo vision method using a single three-charge-coupled-device (3CCD) color camera, which can fully utilize the spatial resolution of the camera sensor of the color camera. However, the color stereo vision method also cannot provide high-spatial-resolution results when the imaging speed is high.

An effective method to overcome the limitation of the image resolution by the acquisition speed is to use camera array imaging, which triggers the cameras to capture images at different times. For the camera array imaging method, Cranz and Schardin [14] proposed a waiting-type framing high-speed camera system with multi-spark equipment. With the development of light-source and high-speed photography technologies, the conventional multi-spark camera system has been improved using a LED light source and CCD camera [15, 16], which had the advantages of electronic control and online image processing. Bennett et al. [17] investigated the capabilities of the digital camera array system by fabricating a large camera array with simple cameras, lenses, and mountings. They demonstrated that the camera array system can not only overcome the inherent disadvantages of high-speed cameras but also it is highly cost-effective. The camera array method was applied to two-dimensional (2D) digital image correlation (DIC) to investigate the dynamic fracture behavior of crack initiation and propagation in poly(methyl methacrylate) (PMMA) specimens under a low-speed impact [18], which demonstrated the excellent performance of the camera array in 2D DIC measurements.

Although many studies have been performed on the design and application of camera array systems, they have been employed only for 2D deformation measurements. To the best of our knowledge, a dynamic 3D measurement using a camera array system has not yet been reported; it

---

* Corresponding author.
E-mail address: kaizhong@hust.edu.cn (K. Zhong).

https://doi.org/10.1016/j.optlaseng.2018.03.009
Received 14 January 2018; Received in revised form 9 March 2018; Accepted 9 March 2018
0143-8166/© 2018 Elsevier Ltd. All rights reserved.

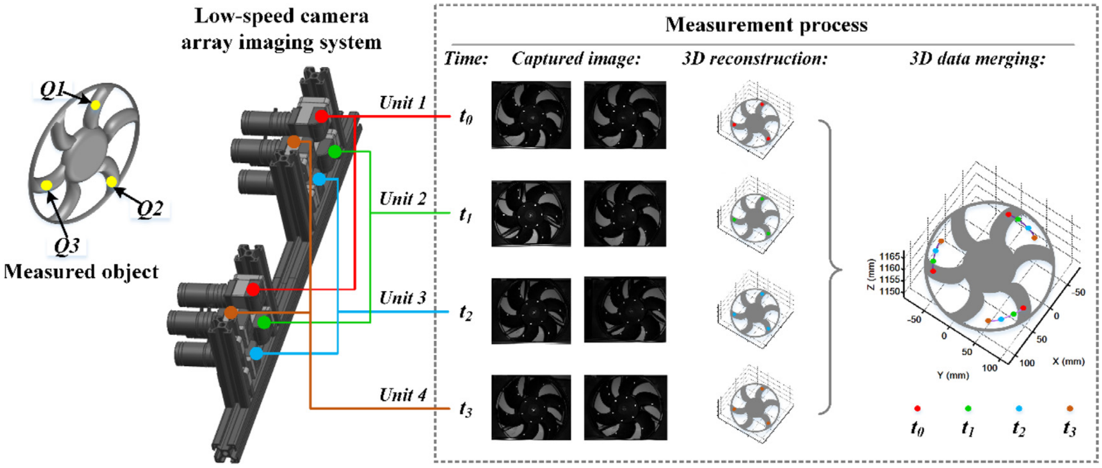


Fig. 1. Measurement principle employed to determine high-speed vibrations using the low-speed-camera array.

has large potentials to be one of the optimal solutions to achieve a high-speed high-resolution 3D measurement. For this purpose, a low-speed-camera-array imaging method for high-speed 3D deformation measurements is proposed in this paper. In order to achieve accurate and stable 3D measurements, a bundle-adjustment-principle-based system calibration method is proposed. The accuracy and effectiveness of the proposed method are demonstrated by accuracy and repeatability experiments, vibration measurement of a plastic board, and out-of-plane displacement measurement of rotating blades.

2. Principles

The principle of the low-speed-camera-array-based high-speed 3D deformation measurement method is illustrated in Fig. 1. In this study, the camera array consists of eight cameras, divided into left and right groups. Each camera in the left group with its corresponding camera in the right group (as shown in Fig. 1) form a single stereo vision unit; therefore, a total of four units are obtained. During the measurements, the stereo vision units are triggered sequentially at different times; therefore, the 3D points of the object can be measured at a very high speed, at most three times faster than one stereo vision unit, when it measures in a loop. It should be noted that this method can be extended to use more cameras in the camera array, so that the measurement speed can be even higher. If each stereo vision unit measures only once, the measurement speed of the system can theoretically reach infinity regardless of the number of cameras.

As described above, the camera array system is composed of several stereo vision units; each unit is composed of two cameras. The camera can be modelled by a standard pin–hole model. An arbitrary 3D point $\mathbf{P}$ in the world coordinate system is denoted as $\mathbf{P}_w$; the ray departing from $\mathbf{P}$, passing though the ith camera lens, is captured on the camera sensor plane to form the image point $\mathbf{p}_i$. In practice, the lens aberrations distort the shape of the images; the imaging process can be described with a nonlinear camera model [19]:

$$\begin{cases} s_i\tilde{\mathbf{p}}'_i = \mathbf{A}_i\left[\mathbf{R}_i|\mathbf{T}_i\right]\tilde{\mathbf{P}}_w \\ \mathbf{p}_i = \mathbf{p}'_i + \theta(\mathbf{k}_i;\mathbf{p}'_i) \end{cases} \tag{1}$$

where $\tilde{\bullet}$ is the homogenous coordinate, s_i is a scale factor, $\mathbf{p}'_i$ is the ideal non-distortion image point, $\mathbf{A}_i$ is the intrinsic camera matrix, $\theta(\mathbf{k}_i;\bullet)$ is the lens distortion parameterized by the distortion coefficients $\mathbf{k}_i$, and $\mathbf{R}_i$ and $\mathbf{T}_i$ are the rigid rotation matrix and translation vector, respectively, which are referred to as extrinsic parameters. As the stereo vision unit contains two cameras, fixed with respect to each other, a rotation matrix $\mathbf{R}$ and translation vector $\mathbf{T}$ can be introduced to represent the relative rigid motion between the cameras.

Before the 3D reconstruction, the corresponding points between stereo views should be identified; the image point $\tilde{\mathbf{p}}_1$ in one camera image that corresponds to an image point $\tilde{\mathbf{p}}_2$ in the other camera image can be determined by the epipolar constraint:

$$\tilde{\mathbf{p}}_1^{\mathrm{T}}\mathbf{F}\tilde{\mathbf{p}}_2 = \mathbf{0}, \mathbf{F} = \mathbf{A}_1^{\mathrm{T}}\mathbf{R}[\mathbf{T}]_{\mathrm{x}}\mathbf{A}_2. \tag{2}$$

where $\mathbf{F}$ is the fundamental matrix, and $[\mathbf{T}]_{\mathrm{x}}$ is the skew symmetric matrix of $\mathbf{T}$. In general, one camera coordinate system can be used as a reference, and the 3D coordinate of the homogenous measurement point $\mathbf{P}_w$ can be reconstructed by a least-squares solution according to Eq. (3):

$$\begin{cases} s_1\tilde{\mathbf{p}}_1 = \mathbf{A}_1[\mathbf{I}|\mathbf{0}]\tilde{\mathbf{P}}_w \\ s_2\tilde{\mathbf{p}}_2 = \mathbf{A}_2[\mathbf{R}|\mathbf{T}]\tilde{\mathbf{P}}_w \end{cases}, \tag{3}$$

where $\mathbf{I}$ is a 3×3 identity matrix, and s_1, s_2, $\mathbf{A}_1$, $\mathbf{A}_2$, $\mathbf{R}$, $\mathbf{T}$ can be accurately calibrated before measurements, as described in Section 3.

In the measurement process, the 3D results of an object at different times computed by stereo vision units should be transformed into a unified coordinate system; the transformation process is shown in Fig. 2. In each unit, the 3D result is computed at its own coordinate system. Once the rotation matrix $\mathbf{R}_{c,\,i}$ and translation vector $\mathbf{T}_{c,\,i}$ between the world coordinate system and measurement coordinate system of the ith unit are accurately calibrated, the 3D points $\mathbf{P}_{c,\,i}$ measured by the ith unit can be transformed into the world coordinate system:

$$\mathbf{P}_w = \mathbf{P}_{c,i}\mathbf{R}_{c,i} + \mathbf{T}_{c,i}. \tag{4}$$

3. Camera array calibration

The camera array calibration procedure consists of stereo vision unit calibration and pose calibration of each stereo vision unit. In order to achieve an accurate 3D measurement, a bundle-adjustment-principle-based calibration method is proposed. In this method, a planar calibration target with pre-defined circular features is placed freely in the measurement volume at several positions; at each position, all of the cameras can simultaneously capture calibration target images, as all of them have the same field of view. The calibration target placement number should be theoretically larger than three; when this number increases, more accurate and stable calibration results can be obtained. In our method, this number is set to 12. After the acquisition of all of the images, the parameters and pose of each stereo vision unit can be computed.

3.1. Stereo vision unit calibration

In the stereo vision unit calibration computation, the intrinsic parameters of each camera are initially obtained by the prevailing Zhang's method [20]; however, this method requires accurately manufactured

Download English Version:

https://daneshyari.com/en/article/7131558

Download Persian Version:

https://daneshyari.com/article/7131558

Daneshyari.com