Optics and Lasers in Engineering 113 (2019) 14–22

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

A new microscopic telecentric stereo vision system - Calibration, rectification, and three-dimensional reconstruction

Yan Hu[a,b], Qian Chen[a], Shijie Feng[a,b], Tianyang Tao[a,b], Anand Asundi[c], Chao Zuo[a,b,*]

[a] Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China
[b] Smart Computational Imaging (SCI) Laboratory, Nanjing University of Science and Technology, Nanjing, Jiangsu Province 210094, China
[c] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore

ARTICLE INFO

Keywords:
Three-dimensional sensing
Binocular and stereopsis
Epipolar geometry
Optical metrology

ABSTRACT

In stereo vision based three-dimensional (3D) measurements, calibration and stereo matching are the most challenging tasks for accurate 3D reconstruction. In this paper, a new microscopic telecentric stereo vision system is proposed to retrieve 3D data of micro-level objects by direct triangulation from two accurately calibrated telecentric cameras. The complex projector calibration procedure commonly seen in traditional structured-light based systems can be avoided. Besides, an improved and practical calibration framework of telecentric cameras is presented. Compared with existing calibration methods which retrieve the distortion parameters without reasonable initial guesses, our proposed approach derives reliable initial guesses for all the camera parameters to avoid the local minima problem based on the estimation algorithms before iterations. To realize precise sub-pixel stereo matching, we propose an effective searching algorithm based on the epipolar rectification of the absolute phase maps obtained from fringe projection profilometry. Experimental results indicate that a measurable volume of 10 mm (L) × 7 mm (W) × 7 mm (H) is achieved with the standard deviation of 1.485 μm.

1. Introduction

In recent years, advances in precision manufacturing demand micro-level three-dimensional (3D) metrology to guarantee accurate fabrication and optimal designs. As a classic passive 3D measurement technique, stereo vision measurement has been extensively used for topometry of a wide range of surfaces [1]. However, correspondence (stereo matching), which tries to find the corresponding parts in multi-views remains as one main challenge in passive stereo vision measurement because the physical features are usually not readily detectable and distinguishable [2]. A practical solution is to use active markers for accurate stereo matching.

As a widely used non-contact method for surface profiling, structured-light projection technique can provide full-field active markers [3,4]. In traditional structured-light based systems, a digital projector is employed to create required artificial fringe patterns and considered as one view for stereo-measurement [5]. Appropriate calibration of a projector based multi-view system is vital for accurate 3D reconstruction [6,7]. For micro-3D measurement, the smaller field of view (FOV) in the microscopic multi-view system necessitates auxiliary lenses. One approach is to adopt a stereo-microscope for this task [8]. However, because of the complicated optics inside a stereo-microscope, calibration of such an optical system with a flexible method [6] is difficult. The second approach is to use telecentric lenses owing to their increased depth of field and constant magnification along the optical axis [9]. Initial studies using telecentric lenses for micro-3D topometry were based on a single-camera configuration [10–14]. However, the projector in these systems needs calibration with the help of a calibrated camera, which is a complex process. Besides, the calibration accuracy cannot be guaranteed due to the unpredictability caused by the gamma effects, lens distortion, and the misalignment of the additional auxiliary lens in the projector. To utilize the advantage of full-field active markers provided by the projector and avoid being bothered by the issues related to the projector, a potential solution is to design a stereo vision system that comprises two well-calibrated telecentric cameras for stereo matching and one projector for active marker projection.

In this paper, a microscopic telecentric stereo vision system is introduced to overcome the challenges of system calibration and stereo matching. The calibration procedure only involves two telecentric cameras without the necessity to calibrate the projector; therefore, the complexity of the projector calibration and other issues in single-camera based systems can be effectively avoided. For the telecentric camera calibration, many approaches have been proposed. Li and Tian [15] proposed a planar calibration technique which however does not consider the ambiguity of the extrinsic parameters. Chen et al. [16] addressed

* Corresponding author at: Nanjing Univ. of Science and Technology, Xiao Ling Wei Street #200, Nanjing, Jiangsu, 210094, China.
E-mail addresses: chenqian@njust.edu.cn (Q. Chen), anand.asundi@pmail.ntu.edu.sg (A. Asundi), zuochao@njust.edu.cn (C. Zuo).

https://doi.org/10.1016/j.optlaseng.2018.09.011
Received 21 May 2018; Received in revised form 12 September 2018; Accepted 14 September 2018

this shortcoming by capturing image pairs along the depth axis for each posture of the calibration board to unambiguously recover the rotation matrix. However, the distortion center is not calibrated for the intrinsic parameters of the camera. Rao et al. [17] also proposed a method that directly uses the pinhole model to describe the imaging process of the telecentric camera, which may fail for lenses with good telecentricity. Different from the pinhole cameras, the distortion center (projection center) of a telecentric camera locates at infinite so that it is hidden in the distortion-free camera model and can be only derived through iterations.

To better calibrate the distortion of a telecentric camera, we have to know the position of the distortion center correctly. In Yao's work [18], a novel two-step calibration procedure to get the full-scale parameters including the distortion center by two non-linear optimization processes is proposed. However, in their method, the detector's center is assumed as the initial value of the distortion center. Because the full-scale camera parameters are all estimated together in each optimization step, the search process from the detector's center is prone to find a local minimum when the actual distortion center is not close enough to the detector's center. To solve this problem, we propose an improved and efficient calibration framework for telecentric cameras in this paper. Compared with the state-of-the-art methods that ignore or assume initial guesses for the distortion parameters before the iterations, the proposed method uses a two-step estimation algorithm to decouple the distortion center calculation from the full-scale parameters optimization. The initial guesses of distortion coefficients are also effectively estimated before the iteration. With these trustworthy initial guesses, a more robust calibration framework is achieved, and thus the probability of being trapped in local minima is significantly decreased.

In the stereo matching step, telecentric epipolar rectification of the calibrated telecentric stereo vision system is performed to facilitate the matching process. Firstly full-field phase maps are obtained as in the traditional manner. After the distortion compensation and epipolar rectification of the phase maps, all the points of the measured scene lie in the same vertical position in the two images. Thus by searching the pixel with the closest phase value and inverse linear interpolation, subpixel stereo matching of the two telecentric cameras can be efficiently achieved.

In this paper, the overall processes of the system calibration, epipolar rectification, and 3D reconstruction using our microscopic profilometry system are detailed in Sections 2–4, respectively. The simulation result shows that with the reliable camera parameters acquired based on trustworthy initial guesses, the re-projection error can be reduced by one order of magnitude or so. The experiments also demonstrate that the proposed stereo matching method based on epipolar rectification of the full-field and high-resolution phase maps accommodates the measurements for various kinds of objects with a sizeable measurable depth. Finally, the conclusion and suggestion for future work are summarized to close this paper.

2. Telecentric camera model and telecentric epipolar rectification

2.1. Telecentric camera model

Unlike the perspective projection in the imaging process of a pinhole camera, telecentric cameras provide purely orthographic projections of the scene, which makes it easier to measure physical size independently from depths. The imaging model of a distortion-free telecentric camera is illustrated in Fig. 1. (x_w, y_w, z_w) and (x_c, y_c, z_c) are the coordinates of an arbitrary object point $\mathbf{P}$ in the world coordinate system $O - X_W Y_W Z_W$ and camera coordinate system $O_C - X_C Y_C Z_C$, respectively. Because of the affine projection from the camera coordinate to the image coordinate, the camera center O_C of a telecentric camera locates at infinite. $\mathbf{p}(u, v)$ is the image coordinate of point $\mathbf{P}$ and $\mathbf{e}(u_0, v_0)$ is the image coordinate of the optical center, which is also known as the distortion center and usually does not coincide with the detector's center (image center). The aperture stop is used to assure the telecentricity of the lens [19].

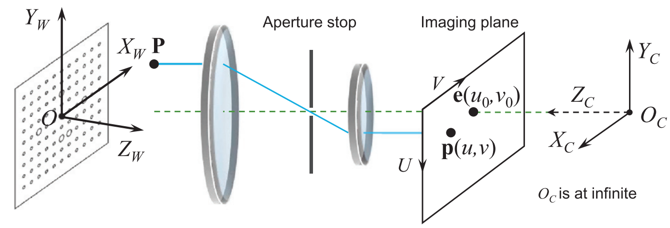

Fig. 1. Simplified schematic of the imaging process and the coordinate systems of a telecentric camera.

For the object point $\mathbf{P}(x_c, y_c, z_c)$ in the camera coordinate system, its homogeneous image coordinate $\tilde{\mathbf{p}}$ is projected in an affine form as

$$\begin{bmatrix} \mathbf{p} \\ 1 \end{bmatrix} = \begin{bmatrix} m & 0 & u_0 \\ 0 & m & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ 1 \end{bmatrix}, \tag{1}$$

where m is the effective magnification of the telecentric lens. For an ideal telecentric camera, u_0 and v_0 can be set as zeros. Each calibration pattern has it own world coordinate system. The pattern on the calibration board determines X_W and Y_W as well as the original point O. The world and camera coordinate systems are related by a rotation matrix $\mathbf{R}$ and a translation vector $\mathbf{t}$ as

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \mathbf{R} \begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} + \mathbf{t}. \tag{2}$$

Here, $\mathbf{R} = [\mathbf{r}_x\ \mathbf{r}_y\ \mathbf{r}_z]^{\mathrm{T}}$ and $\mathbf{t} = [t_x\ t_y\ t_z]^{\mathrm{T}}$. The whole projection of a point $\mathbf{P}(x_w, y_w, z_w)$ in the world coordinate to an image point $\mathbf{p}(u, v)$ can be expressed as [15]

$$\begin{bmatrix} \mathbf{p} \\ 1 \end{bmatrix} = \mathbf{A} \begin{bmatrix} \mathbf{R}_{2\times3} & \mathbf{t}_{2\times1} \\ \mathbf{0}_{1\times3} & 1 \end{bmatrix} \begin{bmatrix} \mathbf{P} \\ 1 \end{bmatrix} = \mathbf{H} \begin{bmatrix} \mathbf{P} \\ 1 \end{bmatrix}, \tag{3}$$

Here,

$$\mathbf{A} = \begin{bmatrix} m & 0 & u_0 \\ 0 & m & v_0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{4}$$

and $\mathbf{H}$ is the homography matrix, which transforms the world coordinates of objects into their corresponding image coordinate.

2.2. Telecentric epipolar rectification

The epipolar geometry of two telecentric cameras is similar to that of two pinhole cameras. A pixel $\mathbf{p}_L(u_L, v_L)$ in the left view corresponds to an epipolar line in the other view, on which the matched pixel $\mathbf{p}_R(u_R, v_R)$ meets an the affine epipolar constraint equation as [20]

$$au_R + bv_R + cu_L + bv_L + e = 0, \tag{5}$$

where, $a \sim e$ are five constants. As shown in Fig. 2(a), pixel $\mathbf{p}_{L_1}$ on the left camera corresponds to an epipolar line l_R, on which a pixel $\mathbf{p}_{R_1}$ also corresponds to an epipolar line l_L. The telecentric stereo images can be rectified to make the matched pixel pairs in the same vertical position to facilitate the stereo matching of the stereo vision system as shown in Fig. 2(b). The original images need to be transformed into new ones, and thus a new set of camera parameters is acquired. Different from calculating the fundamental matrix between two views [21], we first calibrate the cameras with two set of parameters for each camera and then rectify them. Here we use a prime to represent the new parameters and add subscript "L" or "R" to distinguish the left and right cameras.