

Camera calibration with active phase target: improvement on feature detection and optimization

Lei Huang,^{1,*} Qican Zhang,^{1,2} and Anand Asundi¹

¹School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798

²Department of Opto-electronics, Sichuan University, Chengdu 610065, China

*Corresponding author: huanglei0114@gmail.com

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The calibration of camera with intrinsic and extrinsic parameters is a procedure of significance in current imaging-based optical metrology. Improvement at two aspects, feature detection and overall optimization, are investigated here by using an active phase target and statistically constrained bundle adjustment (SCBA). From the observations in experiment and simulation, the feature detection can be enhanced by “virtual defocusing” and windowed polynomial fitting if sinusoidal fringe patterns are used as the active phase target. SCBA can be applied to avoid the difficult measurement of the active target. As a typical calibration result in our experiment, the root mean square of reprojection error can be reduced to 0.0067 pixels with the proposed method. © 2013 Optical Society of America
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As a major portion in optical metrology, imaging-based optical measurement techniques are widely applied in today’s metrology industry due to its fast, full-field, and non-scanning properties [1]. In these imaging-based techniques, the digital camera is universally adopted as an image recording device owing to its convenience in image capture and photo storage, as well as data transmission. For measurement purposes, the digital camera must be calibrated in advance to achieve the desired measuring accuracy. Since the quality of the camera calibration directly influences or even determines the performance of the metrology system, many recent research efforts have been made to investigate how to calibrate the camera with higher accuracy [2–7].

The initial study on calibration of camera starts by using three-dimensional (3D) calibration targets, which are difficult to manufacture or measure with high accuracy [8,9]. Instead of using 3D targets, Tsai pioneered using a two-dimensional (2D) calibration target with accurate out-of-plane shifts [10]. Zhang proposed a flexible camera calibration approach that allows the 2D calibration target to be placed arbitrarily [7].

There is a trend in optimization of estimating the camera parameters and the target geometry simultaneously [3,5]. An iterative optimization was proposed by Albarelli *et al.* to estimate the camera parameters and target geometry in which the estimations for camera parameters and target geometry are decoupled in each iteration [5]. Strobl and Hirzinger estimated camera parameters and target geometry simultaneously by presetting geometric constraints with measurement values [3].

The other trend is to improve the accuracy of feature detection. Vo *et al.* experimentally confirmed that the enhancement of the accuracy of feature detection improves calibration accuracy by applying the digital image correlation method on the frontal image after a preliminary calibration [2]. Another way to advance the feature detection is to utilize an active calibration target, as shown in Fig. 1. A method to calibrate wide-angle lens distortion by

using structured-light illumination on a display was proposed by Sagawa *et al.* [11]. Moreover, Schmalz *et al.* make a comparison of camera calibration with an active target and a passive target, and convincing results show the superiority of an active target [4].

It should be noted that there is obvious potential for calibrating cameras with active targets due to following advantages: (a) the feature detection is both accurate and precise owing to the advance of the fringe analysis technique [12], (b) the image defocusing will have little influence if sinusoidal stripes are adopted as the calibration pattern, and (c) nowadays it is easy to get a display with a relatively high flatness.

However, from our observation, active-target-based calibration still has some limitations, and the corresponding improvements can be made to perfect the current technique.

(1) During the calibration, the target should be placed within the desired volume of interest, commonly in the

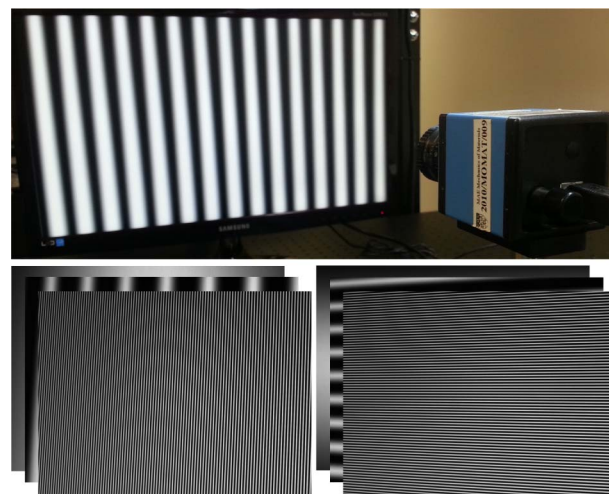


Fig. 1. Sinusoidal fringe patterns displayed on an LCD screen can be used as active targets for camera calibration.

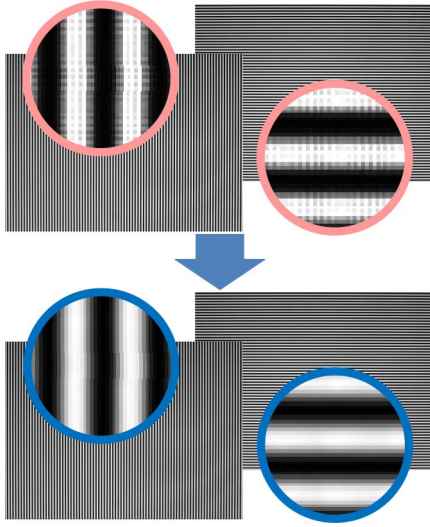


Fig. 2. Pixel grids in focus can be removed by using the VD method.

depth of focus. However, when the active phase target is in the depth of focus, the pixel grids on the display are unavoidably recorded, which will affect the subsequent feature detection.

If sinusoidal stripe patterns are utilized as the calibration pattern, an approach called “virtual defocusing” (VD) can be applied to solve the issue of “grids in focus,” as shown in Fig. 2. In implementation, convolution with a Gaussian filter can be applied to the fringe patterns.

As shown in Fig. 3, the fringe phase can be retrieved with a higher precision after the preprocessing and the phase accuracy maintains at the same level. The ground truth of phase values can be obtained by applying the 2D windowed Fourier transform method on the retrieved phase with the phase-shifting technique [13]. The root mean square (RMS) of the phase error is reduced from 0.0706 rad ($\approx 1/100$ of 2π) to 0.0041 rad ($< 1/1000$ of 2π) as a typical experimental record in our investigation.

(2) When an active phase target is used, the feature detection will benefit from the advanced fringe analysis technique, but the precision of the feature detection can be further improved with windowed polynomial fitting on the relations of $x = f_x(\varphi_x, \varphi_y)$ and $y = f_y(\varphi_x, \varphi_y)$.

A typical simulation result in Fig. 4 demonstrates that, when the RMS of phase retrieval error is $1/1000$ of 2π (≈ 0.00628 rad), the RMS of the detection error can be effectively reduced from 0.02624 pixels with linear interpolation down to 0.00077 pixels by biquadratic fitting

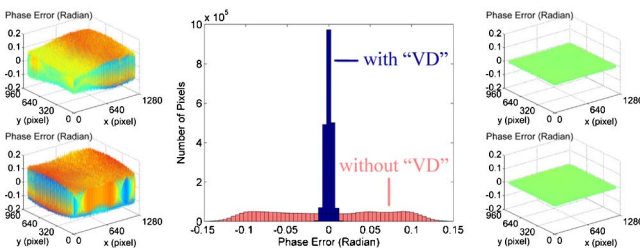


Fig. 3. VD method improves the precision of phase measurement. Distributions of phase errors without VD (left) and with VD (right), and the error histogram (middle).

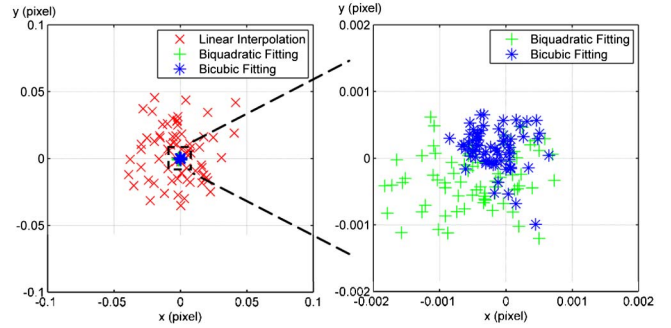


Fig. 4. Windowed polynomial fitting highly enhances the feature detection.

(about 34 times improvement), or even 0.00044 pixels by bicubic fitting (about 60 times improvement).

(3) The calibration result will be more accurate if the target geometry is involved in the optimization, which commonly needs constraints from actual measurement. However, it is difficult to accurately measure the geometry of an active target, e.g., an LCD screen. A method called statistically constrained bundle adjustment (SCBA) is applied to simultaneously estimate the camera parameters and the target geometry without measuring the active target:

$$[\mathbf{P}^*, \mathbf{T}_n^*, \mathbf{X}_{wm}^*] = \arg \min_{(\mathbf{P}, \mathbf{T}_n, \mathbf{X}_{wm})} \sum_{n=1}^N \sum_{m=1}^M \|\mathbf{m} - f(\mathbf{P}, \mathbf{T}_n, \mathbf{X}_{wm})\|^2, \quad (1)$$

where \mathbf{m} is the image coordinates, \mathbf{P} is the camera intrinsic parameters, \mathbf{T}_n is the extrinsic parameters, and \mathbf{X}_{wm} is the geometry of the model in the world coordinates. The constraints are applied by

$$\begin{aligned} \sum_m^M \mathbf{X}_{wm}^* &= \sum_m^M \mathbf{X}_{wm}, \\ \mathbf{n}_x^* &= 0, \mathbf{n}_y^* = 0, \\ \sum_m^M x_{wm}^* y_{wm} - x_{wm} y_{wm}^* &\rightarrow 0, \\ \sum_m^M \|\mathbf{X}_{wm}^* - \mathbf{X}_{wm}\|^2 &\rightarrow 0. \end{aligned} \quad (2)$$

These constraints are not determined from the measured geometric values but from the global knowledge of the designed calibration pattern in a statistical sense.

The optimization of camera parameters without estimation of the target geometry is first carried out. The target geometry is then involved in the overall optimization with the SCBA method. Usually, the calibration is assessed by the projection of the feature points onto the image coordinates. The RMS of reprojection error is effectively diminished from 0.0250 pixels to 0.0067 pixels (about 4 times improvement in reprojection precision) as a typical record shown in Fig. 5. They are much smaller than the acceptable reprojection error in day-to-day calibration or even smaller than very careful calibration records in literature [4].

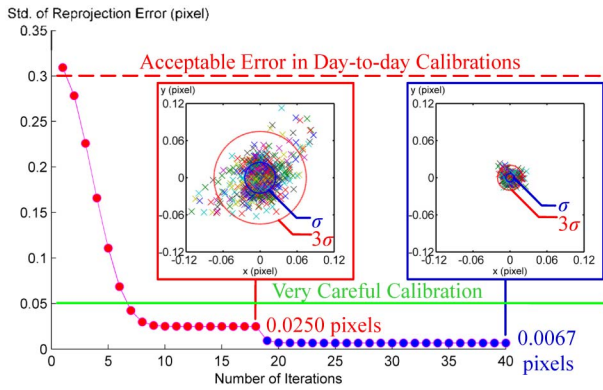


Fig. 5. With the advanced feature detection, the reprojection errors can be reduced to 0.025 pixels or even less, as 0.0067 pixels, if SCBA is applied.

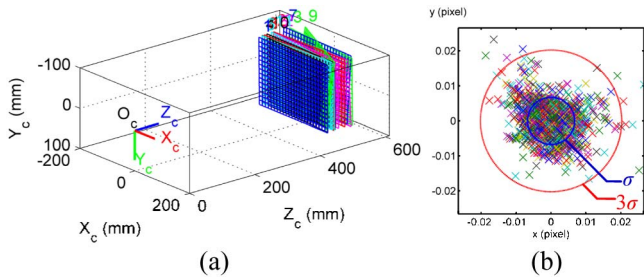


Fig. 6. Experiment is carried out to calibrate a camera with the proposed method. (a) The screen poses and (b) the distribution of reprojection error.

To verify the methods proposed above, a practical camera calibration is carried out. The camera to calibrate is a CCD sensor (Imaging Source DMK 41BU02 with a resolution of 1280×960 pixels) with a 16 mm lens (Computar M1614-MP2). An LCD monitor (SAMSUNG S23B350H with a resolution of 1920×1080 pixels and pixel pitch of 0.2655 mm) with a series of designed sinusoidal fringe patterns is used as the active target. In the experiment, as shown in Fig. 6(a), the monitor is placed at 12 different poses for the calibration.

The multifrequency fringe analysis technique [12,14] is adopted for phase retrieval with fringe numbers of 1, 15, and 240 in the x direction and 1, 15, and 135 in the y direction, and hence the finest fringe period in either the x or y direction is 8 pixels. For each frequency,

eight-frame phase-shifted fringe patterns are used to get rid of the influence of nonlinearity as much as possible [15]. A 6×6 pixel Gaussian filter with a standard deviation of 1 pixel is utilized to virtually defocus the captured sinusoidal fringes. In total, 24×16 feature points are detected by using the windowed bicubic fitting with a window size of 200×200 pixels. The SCBA method is applied after the traditional estimation with the detected feature points to reduce the reprojection error, and, as shown in Fig. 6(b), the RMS of the resultant reprojection error is 0.0067 pixels in our experiment.

A technique with an accurate feature detection method by using an active phase target and a SCBA method is proposed to improve the existing camera calibration. Simulation and experimental results verify the proposed technique. The RMS of the reprojection error can be reduced to 0.0067 pixels as our experimental result.

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