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A holistic calibration method with iterative distortion compensation for stereo deflectometry

Yongjia Xu[a], Feng Gao[a,*], Zonghua Zhang[a,b], Xiangqian Jiang[a]

[a] EPSRC Center, University of Huddersfield, HD1 3DH, UK
[b] School of Mechanical Engineering, Hebei University of Technology, Tianjin 300130, China

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ABSTRACT

This paper presents a novel holistic calibration method for stereo deflectometry system to improve the system measurement accuracy. The reconstruction result of stereo deflectometry is integrated with the calculated normal data of the measured surface. The calculation accuracy of the normal data is seriously influenced by the calibration accuracy of the geometrical relationship of the stereo deflectometry system. Conventional calibration approaches introduce form error to the system due to inaccurate imaging model and distortion elimination. The proposed calibration method compensates system distortion based on an iterative algorithm instead of the conventional distortion mathematical model. The initial value of the system parameters are calculated from the fringe patterns displayed on the systemic LCD screen through a reflection of a markless flat mirror. An iterative algorithm is proposed to compensate system distortion and optimize camera imaging parameters and system geometrical relation parameters based on a cost function. Both simulation work and experimental results show the proposed calibration method can significantly improve the calibration and measurement accuracy of a stereo deflectometry. The PV (peak value) of measurement error of a flat mirror can be reduced to 69.7 nm by applying the proposed method from 282 nm obtained with the conventional calibration approach.

1. Introduction

The three-dimensional (3D) shape measurement of objects is becoming increasingly important in many applications. Many optical measurement methods have been developed for the 3D measurement of diffuse objects [1–3]. However, the measurement of specular surface remains a challenge because of the reflecting property. Stereo deflectometry is a technique to obtain the form information of freeform specular surfaces [4–7]. Stereo deflectometry system generally consists of a screen and two cameras. The screen is most commonly a standard liquid crystal display (LCD) attached to a computer and used to display two groups of orthogonal sinusoidal fringe patterns. The patterns are captured by the cameras simultaneously through the reflection of a target surface. By dealing with the deformed patterns, the form of the target surface can be calculated. For each camera, the normal vector of a space point can be calculated based on a triangular relationship consisting of the space point, the image point in the camera, and the corresponding point in the screen. By searching the space point and matching the normals in terms of the two cameras, a primary 3D data and the corresponding normal vectors of the target surface can be obtained. Then the optimized overall shape of the object is integrated based on the normal vectors [8–9].

The normal calculation accuracy and the matching accuracy of normal vectors are very sensitive to systematic errors so the calibration of the stereo deflectometry system plays an important role. Because the screen of the deflectometry cannot be captured directly by the cameras, in order to build the relationship between the cameras and the screen, extra special equipment are introduced for common deflectometry system calibration, such as calibration target [10,11], flat mirror with marker [12–14], and extra cameras and/or screen [15,16]. These equipment not only make the calibration process complex but also bring new error source. Therefore, Werling [17] researched to calibrate a standard deflectometry setup using a flat mirror. Xiao [18] describes a geometrical calibration approach to optimize the relation between the system components by using a markerless flat mirror. Traditional deflectometry calibration approaches [4,5,12,13,19–23] separate the whole system into several components or steps, where each step has to deal with noisy data and the inaccurate result propagated from the previous calibration step. Moreover, system parameters are optimized based on different cost functions in terms of different steps. The error propagation of calibration steps and the inconsistency of optimization functions result in large systematic deviations for the global calibration parameters. Therefore, holistic calibration approaches are researched to enhance calibration accuracy. Olesch and Faber et al. [24–26] proposed a self-calibration method for deflectometry which can reduce the global error of a flat mirror from 3 μm to under 1 μm. By applying the nor-

* Corresponding author.
E-mail address: F.Gao@hud.ac.uk (F. Gao).

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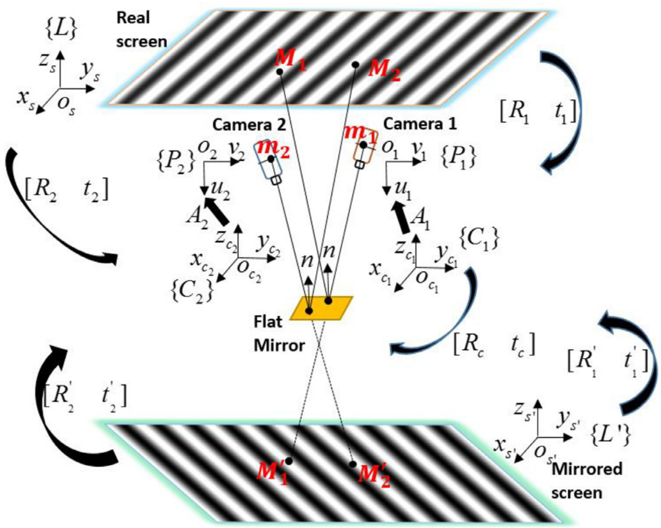

Fig. 1. The illustration of stereo deflectometry.

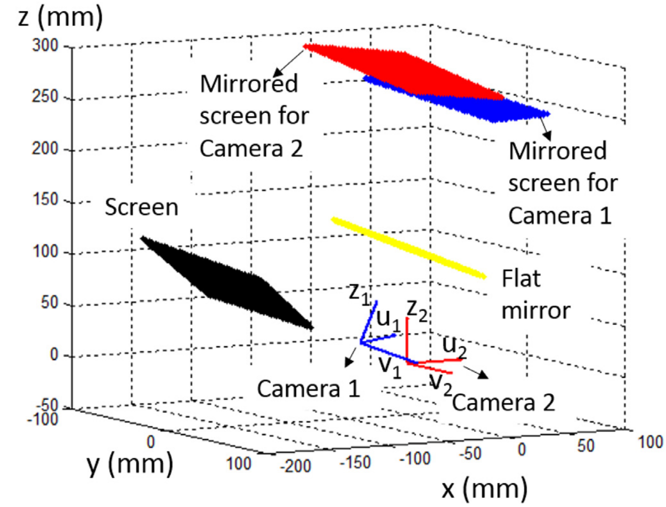

Fig. 3. The simulation setup.

mal vector of an optical flat mirror as an intermediate variable, Ren et al. [27] proposed an iterative optimization calibration approach for a stereo deflectometry. The global measurement error of a 2 in. flat mirror is near 100 nm in their experiment. The calibration approaches mentioned above all apply traditional distortion compensation model researched for camera calibration [28,29] to deal with the distortion in deflectometry. However the accuracy of traditional distortion compensation approach is limited by the matching accuracy between the established mathematical model and the real distortion. Though the accuracy of the conventional approach is acceptable for the general calibration requirement of the system with micron level measurement accuracy, it is one of the error source that hinder the stereo deflectometry to reach nanometer level measurement accuracy. Therefore, it is urgent to research a calibration method that can eliminate distortion more effectively and achieve higher calibration accuracy for stereo deflectometry.

This paper proposes a novel holistic calibration method for stereo deflectometry based on the iterative distortion compensation algorithm proposed by Xu et al. [30]. A markless flat mirror is used to reflect the fringe patterns on the screen to the cameras during the calibration process. Initial system parameters are estimated based on the captured patterns. Then an iterative algorithm is proposed to compensate system distortion. During the iterative process, camera imaging parame-

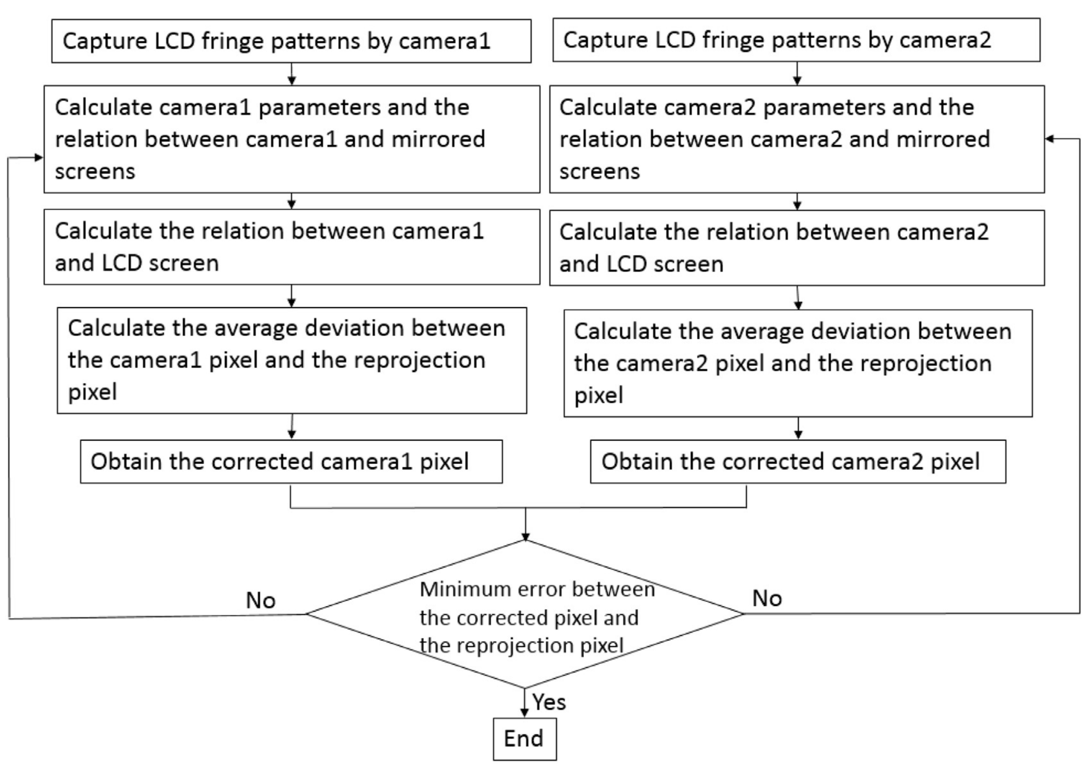

Fig. 2. The flowchart of the proposed calibration method.