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Active Display Registration in Phase Measuring Deflectometry

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Summary:
We present the first experimental realization of phase measuring deflectometry (PMD) with active display registration. A stereo camera system determines the position and shape of the display that is used in PMD for active pattern generation. As an example, we measure the shape of two mirrors.

Keywords: Optical metrology, phase measuring deflectometry, generic camera model, specular surfaces, shape reconstruction

Introduction

Phase measuring deflectometry (PMD) [1] is a robust and low cost full-field shape measurement method for specular surfaces. It is based on the reflection of light rays. A display is showing sinusoidal fringe patterns which are reflected by a surface under test (SUT) and recorded with a camera. Using phase shifting technique, this establishes a correspondence between camera pixels and phase angles of the sine patterns, encoding positions on the display. This phase information is used to determine the shape of the SUT by means of inverse ray tracing.

The phase information does not uniquely determine the shape of the SUT [1]. Regularization is the process of incorporating additional information to make the shape reconstruction feasible. Setups with multiple cameras, with a translation stage moving the display or with a distance sensor provide additional information for regularization.

Active Display Registration in PMD

Bartsch and Bergmann [2] proposed the idea of Active Display Registration (ADR). A schematic setup is depicted in Fig. 1. A stereo camera system observes the PMD display directly to register its position and shape. By moving the display to several distances from the SUT, regularization can be obtained. Because ADR captures the display shape, it has the potential to reduce systematic errors caused by display nonplanarity. Additionally, ADR allows for more freedom in setup geometry as the display is not fixed. This in term may simplify the measurement of SUTs with high curvature or large size.

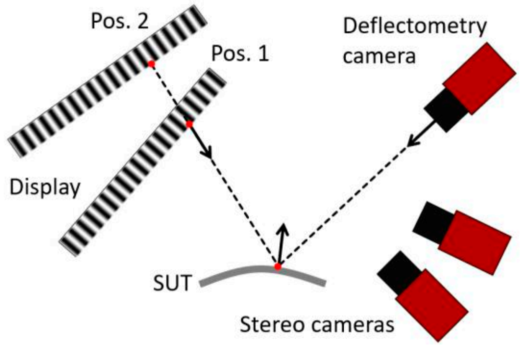

Fig. 1 Schematic of PMD with ADR. The stereo camera pair observes the display. The deflectometry camera observes the display via reflection on the SUT. The display is moved to several positions.

Zhang et al. [3] introduced a similar method based on speckle digital image correlation instead of PMD. However, their method relies on sufficient focus to capture the speckle image, and their setup is limited to the measurement of nearly flat SUTs.

In this paper, we present the first experimental realization of PMD with ADR.

Experimental Setup

Figure 2 shows our setup. All three cameras capture fringe images shown on the display to obtain phase information. Utilizing the principle of fringe projection [4], the stereo camera system determines a mapping from phase to 3D coordinates. This mapping is used to translate the phase measured by each pixel of the deflectometry camera into a 3D reference point. By moving the display to several positions, each deflectometry camera pixel corresponds to multiple reference points, through which a line can be fitted. The line is intersected with the corresponding camera ray of vision to obtain a surface point of the SUT. This procedure is done for all camera pixels, which yields the SUT shape. Each two intersecting lines also yield a surface normal vector, as can be seen from Fig. 1. Because PMD is a high-sensitivity slope measuring technique, we can therefore use integration [1] to improve the result.

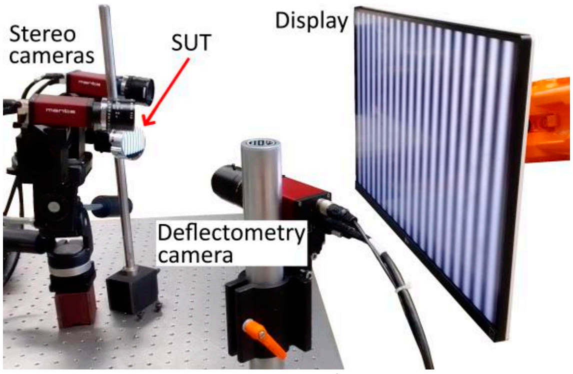

Fig. 2 Experimental setup of PMD with ADR. The display can be moved by a robot manipulator.

Calibration

We describe all cameras with the generic camera model and calibrate them with vision ray calibration [4]. The stereo system cameras are calibrated simultaneously and do not need an extrinsic calibration step for their relative position. The external calibration of the stereo system to the deflectometry camera is achieved with the procedure outlined in [5] using a planar mirror.

Results

We measure the shape of a λ/20 planar mirror and a λ/2 convex spherical mirror. The spherical mirror has a radius of curvature of (201.97±0.02) mm, which was determined with a coordinate measuring machine.

Figure 3 shows the resulting shape deviations. For the planar mirror we obtain a deviation of PV (2±0.03) µm and RMS (0.5±0.03) µm. For the spherical mirror we obtain PV (5.4±0.4) µm and RMS (1.2±0.4) µm. These errors are factor of 2 to 3 higher than that of comparable measurements using an advanced PMD method [6].

The deviations are dominated by low frequency components which indicates systematic errors in the shape measurement. We assume that our current measurement accuracy is essentially limited by the comparatively low resolution of 1.5 MPixel of the stereo system cameras, resulting in a rather sparse mapping of measured phase to 3D coordinates. This uncertainty translates into calibration as well as into shape measurement uncertainty.

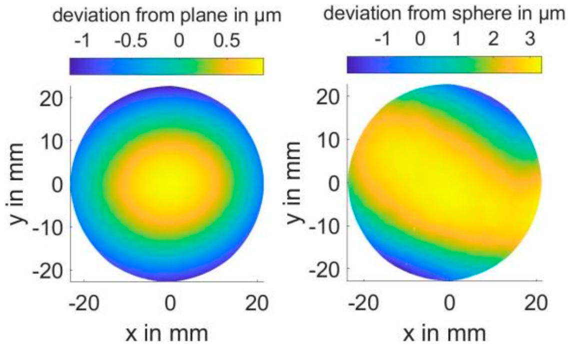

Fig. 3 Shape measurement error. Left: planar mirror (PV 2 µm, RMS 0.5 µm); right: spherical mirror (PV 5.4 µm, RMS 1.2 µm).

Summary and Outlook

We have experimentally realized a phase measuring deflectometry (PMD) setup with active display registration (ADR) and measured the shape of two mirrors. Presently, the PV deviations and the RMS values are a factor of 2 to 3 higher than those of comparable previous measurements [6]. We plan to further investigate systematic errors caused during calibration by independently measuring the tilting of the planar calibration mirror.

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