Hybrid Reflectometry –
3D shape measurement on scattering and reflective surfaces

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The geometric-optical phase measurement techniques Phase Measuring Deflectometry (PMD) and Fringe Projection (FP) can be used for robust, high-precision 3D shape measurements of smooth and rough surfaces, respectively. This article presents an approach for fusing data of PMD and FP measurements, enabling measurement of a wide range of surfaces with mixed reflective behavior.

1 Introduction

By design, the geometric-optical phase measurement techniques (GOP) Phase Measuring Deflectometry (PMD) and Fringe Projection (FP) are used for measurement of objects with diffusely reflective (scattering) and specular reflective surfaces respectively. Real surfaces, such as technical surfaces, show both scattering and specular reflective behavior. Deciding which of these GOP techniques is better suitable for measurement of these surfaces is complicated, for objects with unknown reflection characteristics, it is impossible. In this contribution the Hybrid Reflectometry approach is presented, which allows measurement of surfaces with mixed reflective properties by subsequent PMD and FP measurement and fusion of the measured data.

2 Geometric-optical phase measurement

In both PMD and FP techniques, the object surface to be measured is illuminated with a reference pattern of sinusoidal intensity modulation. The pattern reflected specularly (PMD) or diffusely (FP) on the surface is recorded. Using temporal phase-shifting of the sinusoidal patterns also used in interferometry [1], a mapping of sensor coordinates to pattern coordinates is retrieved, which is termed (geometric-optical) *phase measurement*.

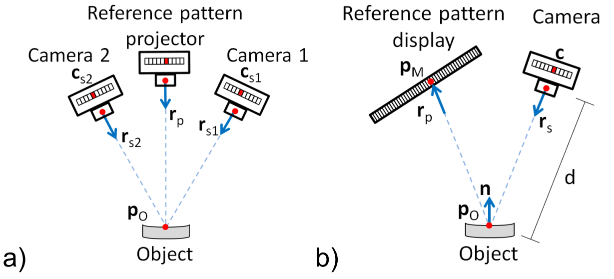

***Fig. 1**: Principles of geometric-optical phase measurement techniques: a) Fringe Projection (FP); b) Phase Measuring Deflectometry (PMD)*

A quality measure for the phase measurement is the fringe modulation M of the recorded sinusoidal pattern, which is proportional to the signal-to-noise ratio *SNR* of the measured phase [2]. While the shape calculation from the phase measurement for FP is performed through triangulation of rays of sight $\boldsymbol{r}_{s1}$, $\boldsymbol{r}_{s2}$ and $\boldsymbol{r}_p$ from cameras and projector (see Fig. 1), PMD delivers an object normal distribution that can be integrated to retrieve the object shape. Opposed to FP, shape calculation from a single phase measurement is underdetermined for PMD, as the reference pattern TFT monitor does not emit light directionally and $\boldsymbol{r}_p$ (see Fig. 1b) is unknown. The corresponding mathematical description is known as the deflectometric problem [3]. The deflectometric problem can be regularized with different approaches, enabling surface normal and shape calculation from PMD phase data. *Stereo PMD* regularization [4] uses phase data from measurements with two cameras from different perspectives to retrieve the object surface normals. For single-camera PMD systems, the *Fixed-Point* regularization makes use of an estimate d_E of the vertical distance d between camera pupil and the object surface for a single point $\boldsymbol{p}_O$ for iteratively calculating the object normals and shape [5]. If a model of the nominal object shape and normal distribution exists, *Ini-Shape* regularization can be used in which d_E, starting from an initial guess, is iteratively varied and the calculated normal distribution is compared to the initial model [5]. For surfaces with both scattering and specular reflective behavior, pixelwise shape data from FP measurements could be used as an initial shape model for iterative evaluation of PMD phase measurements. The combination of FP and PMD systems has been shown in [6], where the data from FP and PMD measurement was evaluated separately. A novel approach performing a fusion of data from PMD and FP measurements is presented here, which shall be termed *Hybrid Reflectometry* (HR) regularization.

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3 Hybrid Reflectometry measurements

A combined Hybrid Reflectometry (HR) test system has been built from PMD and FP system hardware, which consists of reference pattern sources (TFT monitor and projector), one camera for PMD and FP measurements, and an additional camera for stereo FP measurement. With this setup, a measurement of an object surface shown in Fig. 2a with mixed reflective properties (central and outer regions are dominantly specular reflective, low-lying region is scattering) was performed.

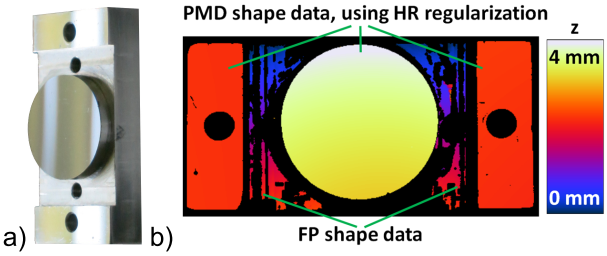

Fig. 2: a) Object surface with locally varying surface roughness; c) Combined shape data from FP and PMD (using HR regularization) measurements, with invalid areas shown in black and colour-coded height (measurement field size: 40 x 20 mm²).

In the scattering surface regions, PMD phase data showed extremely low modulation *M* and thus high phase noise, while in the reflective regions, acceptable values of *M* were retrieved for both PMD and FP measurements. Fig. 2b shows the combined shape data from FP and PMD measurements. with invalid areas shown in black. As the camera image integration time in the FP measurement was adapted to the reflective areas, parts of the scattering object regions were oversaturated, resulting in loss of data. For shape data calculated using HR-regularized PMD, the average value $\overline{\sigma_S}$ of the pixel-wise standard deviation of shape data from repeated measurements was calculated in each region. In the central region $\overline{\sigma_{S1}}$ = 0.31 µm was measured, and in the leftmost and rightmost regions and $\overline{\sigma_{S2}}$ = 3.43 µm was measured, with the latter contributed to global offset between shape data in the individual measurements. This offset indicates the need for an improved orientation between the coordinate systems used for FP and PMD measurement evaluation. In a different measurement series with the HR setup, a spherical mirror (radius of curvature = 200 mm) was measured with the object positioned at different distances to the camera, and a shape fit of the data was performed using a spherical shape model. It was found that shape data calculated using HR-Regularization showed significantly less dependence on the positioning of the object than the shape calculated using the same phase measurement data, but using Fixed-Point regularization with constant d_E (see Fig. 3).

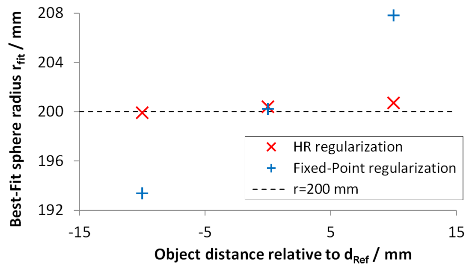

Fig. 3: Radius of best-fit sphere calculated from shape data of spherical mirror (radius of curvature r = 200 mm) with combined HR test system using HR-Regularization and Fixed-Point Regularization with constant d_E (see section 2), for different relative object positions z.

4 Conclusions

First experiments show that the *Hybrid Reflectometry* (HR) approach for calculation of PMD shape data is feasible for measuring object surfaces with mixed specular reflective and scattering properties. Compared to Fixed-Point regularization, the global shape data calculated using the novel HR regularization approach show minimal dependence on the positioning of the object. Future work should be aimed at improving the orientation between coordinate systems used for FP and PMD, and using a single camera also for FP measurement.

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