Highly accurate surface reconstruction for deflectometry

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Deflectometry utilises the deformation of a sample pattern after reflection from a test surface. This yields slope data that must be integrated to obtain surface data, where small geometry errors can add up to significant shape deviations. We demonstrate a new technique to improve the surface reconstruction that uses the known approximate object shape to estimate the distance accurately.

1 Introduction

Deflectometry is a simple but powerful technique to test and measure specular surfaces, where the reflection angles from a test surface reveal local slopes, and thereby, optical imperfections. The slope data can be differentiated into curvature data, enabling sensitivities in the nm range [1]; on the other hand, integrating them into shape data is much more difficult, as the measured surface must have continuous slopes and the geometry of the measurement must be extremely well characterised. Even so, deflectometric surface measurements to less than 1 µm uncertainty are rare. This is one (and possibly the only) reason why deflectometry cannot yet compete with interferometry, although it is in principle much more versatile.

There exist a number of approaches to constrain the reconstruction by extra information [2]. We have previously presented the use of a confocal distance sensor to obtain a valid starting point for the integration [3], whose uncertainty was then taken to be zero.

Further improvement is possible when the approximate shape of the measured surface is known. In this case, the starting point is allowed to be altered by using surface reconstruction results, which must conform to the expected surface to a certain tolerance. Once the starting datum has been set, an unconstrained algorithm reconstructs the surface. We demonstrate a comparison of results from a 200-mm telescope mirror with a tactile reference measurement.

2 Principle

The optimisation algorithm (called IniShape) starts with an estimate of the object distance and an assumption of its shape. Currently, the method can be applied to planes, spheres and parabolic surfaces. (The latter method works because integration errors only take a roughly parabolic shape, and can also be made distinguishable from errors in the optic by a suitable measurement geometry).

Fig. 1 shows an attempt to reconstruct a field of parallel surface normals for a plane object.

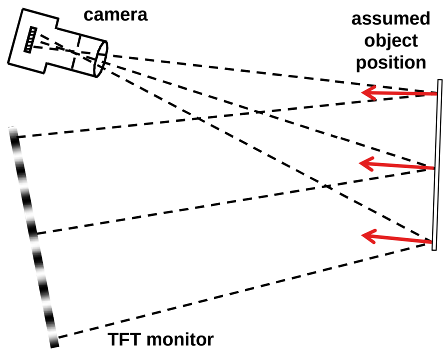

Fig. 1 *First hypothetical object position and resulting inconsistent surface normals.*

It can be seen from this sketch that the assumed object distance is not compatible with a plane object. The surface normals suggest a concave object, which is confirmed by the (calculated) focussing effect upon reflection. Hence, if the object is a plane, it cannot be located at the test position of Fig. 1. On the other hand, Fig. 2 shows a consistent geometry, where the surface normals are parallel, the object is thus a plane, and is also half the size of the screen (the optimal case for measurements of planes).

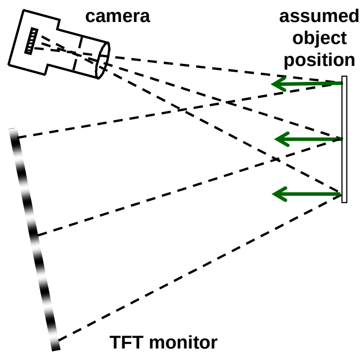

Fig. 2 *Second hypothetical object position and resulting consistent surface normals.*

The technique works in similar ways for spherical and parabolic surfaces. In all cases, a cost function is set up that must be minimised to a certain degree of convergence.

3 Results

An on-axis parabolic telescope mirror surface (∅200 mm) was measured at VEW; its focal length was estimated to be 500 mm. Fig. 3 shows the test piece and a map of the calculated surface curvatures, which is preliminary as long as the object distance has not been determined accurately.

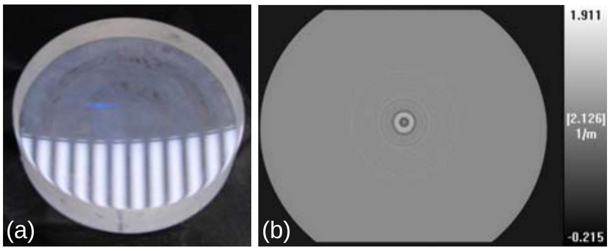

Fig. 3 *(a) Mirror reflecting cosinusoidal measurement fringes; (b) preliminary curvature map.*

The curvature map clearly shows polishing flaws near the centre of the mirror. They would create too large errors in a parabolic fit; therefore they have been masked out in the evaluations. When using an ideal parabolic surface to estimate the measurement geometry, the residuals of the cost function come out as in Fig. 4.

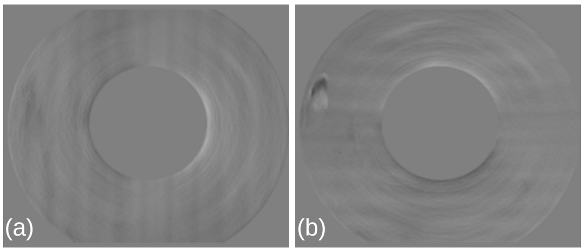

Fig. 4 *(a) Cost-function residual in x direction; (b) cost-function residual in y direction. Scale: –0.2 to +0.2 a.u.*

It is evident that the fitting errors are on the level of the surface flaws and measurement errors, and that the fit is therefore successful. The resulting error map after an unconstrained integration is shown in Fig. 5.

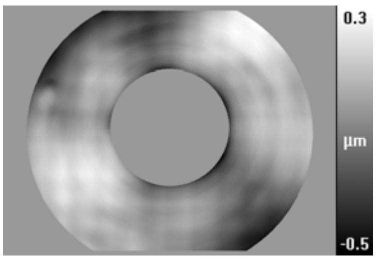

Fig. 5 *Shape deviations from a perfect parabola.*

This result would lend itself to a comparison with an interferometric null test, but unfortunately the focal length, and therefore the path difference in a Fizeau interferometer, is so large as to make this impractical. In any case, interferometry cannot determine the quantity of interest here, namely the focal length, which the test determined to be 517.6 mm – quite a difference to the initial estimate. Therefore the mirror was also measured with a coordinate measurement machine (CMM). Since only a sphere fit was available on the CMM, its result of 1038.10 mm was compared with a sphere fit to the absolute 3-D data from the evaluation presented in Fig. 4 and Fig. 5. The radius of this best-fit sphere was found to be 1037.98 mm; this translates to a maximal profile error of 0.6 µm, which is already in the uncertainty range of the CMM used.

If the distance optimisation is directly carried out with the assumption of a spherical shape, the cost function residuals are distinctly larger, as seen in Fig. 6. This indicates that the fitted surface does not match the real one. The focal length then also comes out incorrectly as 517.0 mm.

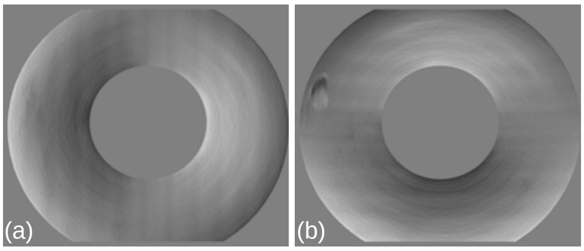

Fig. 6 *(a) Cost-function residual in x direction; (b) cost-function residual in y direction. Scale: –0.2 to +0.2 a.u.*

4 Summary

We have demonstrated a method to exploit the known approximate shapes of tested surfaces for improving estimates of the measurement geometry. The results show that the technique is approaching interferometric uncertainties, with significantly less experimental difficulty and the possibility to extract true 3-D data. This allows accurate determination of radii, focal lengths etc., which again is difficult to do with interferometry. Freeform surfaces will be harder to model for use with this approach, but by no means impossible.

References

[1] M. Knauer, J. Kaminski, G. Häusler, „Phase Measuring Deflectometry: a new approach to measure specular free-form surfaces," Proc. SPIE 5457, 366-376 (2004).

[2] J. Kaminski, "Geometrische Rekonstruktion spiegelnder Oberflächen aus deflektometrischen Messdaten," PhD thesis, University of Erlangen-Nuremberg, ISBN 978-3-932392-86-3 (2008).

[3] M. Sandner, W. Li, T. Bothe, J. Burke, C. v. Kopylow, R. B. Bergmann, "Absolut-Abstandsreferenz für die Streifenreflexionstechnik zur Verringerung systematischer Messfehler," http://www.dgao-proceedings.de/download/112/112_a2.pdf.