Traceable multiple sensor system for measuring curved surface profiles with high accuracy and high lateral resolution

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Abstract. A new scanning system is presented for the high-accuracy form measurement of flat and slightly curved surface profiles. The system employs a small measuring head with multiple distance sensors that is scanned along the surface. Additionally, an autocollimator is utilized to account for angular scanning stage errors. For this setup, suitable design of experiment allows scanning stage errors as well as systematic distance sensor offset errors to be eliminated. As a consequence, high-accuracy form measurements of flat and slightly curved surfaces with high resolution can be achieved. A demonstrator setup has been realized and tested. The results confirm the high potential of this method.
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1 Introduction

In optical surface metrology it is of great importance that the absolute form is measured with high accuracy. The surface forms applied for optical systems are continuously increasing in curvature and complexity. In parallel, the demands on spatial resolution and accuracy are constantly growing. High-accuracy form measurements with high lateral resolution are therefore required. Conventional measurement devices such as coordinate measurement machines (CMMs)[1–4] can satisfy these requirements only partially, and recently, multiple distance sensor systems have been proposed as a promising approach to meet these demands.[5–7] Although "distance" implies a fixed reference, sensors of form measuring setups with arbitrary offset, e.g., Fizeau interferometers, will also be termed distance sensors in the following.

For absolute high-accuracy measurements, the elimination of errors is of first priority. Recent theoretical work[7] has shown that multiple distance sensor systems are basically limited, which means that certain systematic errors cannot be eliminated in principle. For a small sensor head, the cumulation even of small systematic sensor errors leads to large overall errors.[7] As a consequence, a small parabolic or spherical error can sum up to significant form errors, for example, in interferometers used for stitching interferometry. In Ref. 8 it has been recently shown theoretically that additional angular measurements of the sensor system's head can basically solve this problem: the mathematical analysis reveals that for a properly designed multiple distance sensor system supplemented by additional angular information, the elimination of both scanning stage errors as well as systematic sensor offset errors is possible.

In this paper, the experimental realization of the new method is presented. The multiple distance sensor system is realized by an interferometer and angular information is provided by an autocollimator. The system is called a traceable multiple sensor (TMS) system because the measurands of the system can be traced back to the SI units of angle and length with high accuracy.

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2 Mathematical Background of the TMS Principle

In the TMS model,[8] an array of distance sensors with constant spacing is scanned along the surface under test by a scanning stage (see Fig. 1). The analysis of the model accounts for piston and tilt errors, a_i and b_i, of the scanning stage at each position i of the sensor system (see Fig. 2).

In addition, systematic offset errors e_j of the sensor elements are taken into account. The systematic offset errors are assumed to be constant while the sensor system is moved along the specimen. Angular information on the tilt of the distance sensor head is provided by an autocollimator, which is rigidly fixed to the optical table on which the specimen is placed (see Fig. 1). It was shown in Ref. 8 that the surface profile can be reconstructed exactly up to a straight line in the presence of scanning stage piston and tilt errors and systematic offset errors of the distance sensor elements provided that the distance measurements and the angular measurements are noise-free. In the presence of measurement noise, a least-squares solution is applied and the uncertainty of the reconstructed surface profile with respect to measurement noise can be derived. It turns out that the TMS principle yields a stable least-squares solution that reaches high accuracy.

3 Experimental Demonstrator Setup

The multiple distance sensor chosen for the demonstrator setup (see Fig. 3) is a commercial compact Twyman-Green interferometer with an aperture of 3 mm for measuring specular optical surfaces.[9] The pixels of the image detector array within the interferometer represent single distance

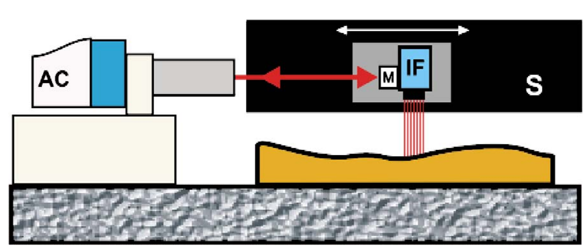

Fig. 1 TMS principle. In this realization, the multiple distance sensor head is an interferometer (IF). It is scanned along the surface under test by the scanning stage S. A mirror (M) is mounted to the side of the sensor head and an autocollimator (AC) measures the tilt angle of the sensor head.

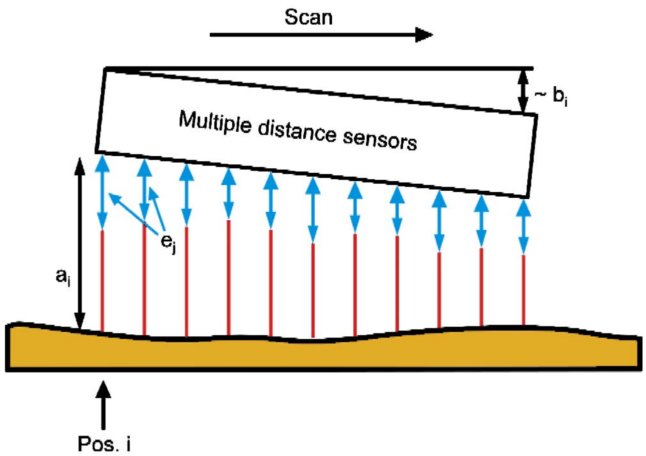

Fig. 2 Error influences having been accounted for in the model: tilt and piston errors, a_i and b_i, of the scanning stage at position i of the sensor system and systematic sensor offset errors e_j of the single sensor elements.

sensors. In the experimental realization, the lateral sensor distance is given by the effective lateral distance of the sensor elements on the specimen's surface. This is given by the image sensor's pixel distance taking into account the magnification of the interferometer's imaging system.

Due to the restrictions in computer capabilities, not all pixels of the interferometer's imaging array were used. Instead, a virtual sensor system consisting of 16 single sensors was constructed from the array as follows. First, a surface was constructed from the interferometer's imaging array by appropriate surface modeling.[10] Then, the obtained surface model was evaluated at the chosen 16 appropriate positions, and the resulting values assigned to the 16 virtual sensors.

The sensor head is scanned along the surface under test by a low-cost linear stage. The specimen can have an extension of up to 300 mm, limited only by the scan range of the scanning stage. The additional angular measurement is carried out by a calibrated autocollimator,[11] which faces a small mirror that is mechanically fixed to the multiple distance sensor. The angle between specimen and autocollimator has to be highly stable, which is achieved by a rigid

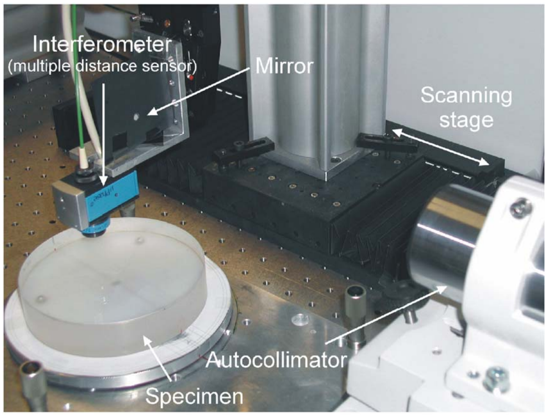

Fig. 3 TMS demonstrator setup with interferometer as multiple distance sensor.

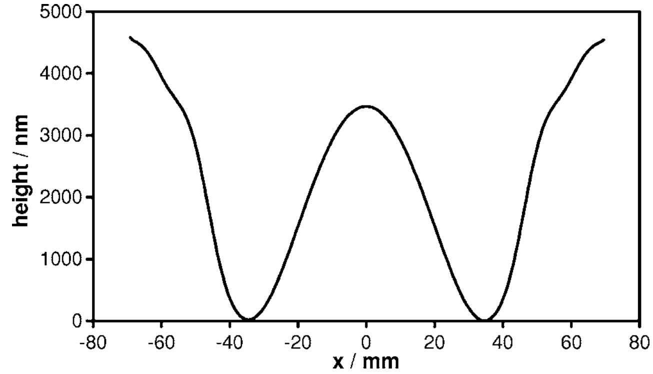

Fig. 4 Measurement result for an aspherical structure on a plane substrate. The profile height is shown along the diameter coordinate x of a rotationally symmetric specimen.

mechanical setup. The measurement is controlled by a standard computer while the data evaluation is performed by an additional fast computer with extended memory capacity.

The TMS model (Ref. 8) implies that the lateral sensor distance is an integer multiple of the scanning step. For the 16 virtual distance sensors formed in this setup, the lateral sensor distance and the scanning step are 0.2 mm, which determines the limit of the lateral resolution of the measurement.

For different demands on the measurement, for example, a higher lateral resolution, the magnification of the interferometer's imaging system, the number of evaluated pixels, and the scanning step can be designed appropriately. Basically, the lateral resolution can be reduced down to a few micrometers for the TMS method using an interferometer as the multiple distance sensor. To further improve the lateral resolution, other sensors could be used, for example, atomic force microscopes.

4 Test Measurements

To test the functionality of the instrument, exemplary surfaces were measured. The reduction of aperture, with respect to full-field interferometers capturing the whole surface in parallel, increases the range of measurable surface slope and curvature. Optical surfaces with peak-to-valley heights of 120,000 nm at a specimen length of 200 mm have been measured with this setup. Figure 4 shows a typi-

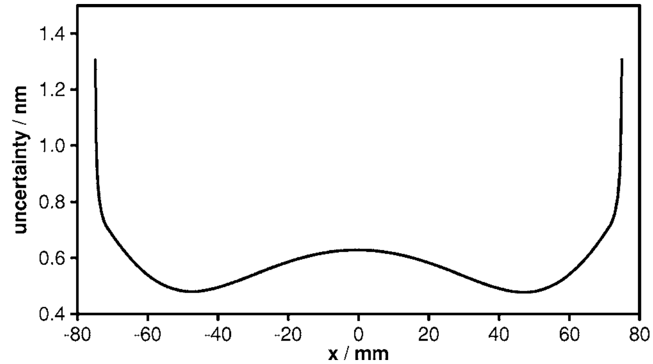

Fig. 5 Uncertainty according to the assumed mathematical model for the measurement shown in Fig. 4.

cal result for an aspherical structure on a flat substrate, and Fig. 5 shows the associated uncertainty with respect to the noise of the measurements. It has to be kept in mind that TMS inherently accounts for scanning stage tilt and piston errors as well as systematic distance sensor offset errors. This means that in contrast to stitching techniques that use distance sensors only, even the parabolic or spherical contributions of the surface form are determined with high accuracy.

To further validate the measurement results of the TMS test setup, comparisons with other measurement principles have been started and will be published soon. The first results confirm the validity of the TMS setup at the uncertainty level of those instruments.

5 Future Tasks

The uncertainty shown in Fig. 5 accounts only for the influence of the noise of the distance and angular measurements assuming correctness of the applied TMS model. Future work will address a more comprehensive uncertainty analysis, taking into account further influences, e.g., possible errors in the lateral positioning of the distance sensor system. First results have already been published.[10,12,13] In particular, the following sources of uncertainty need to be quantitatively assessed:

- Lateral positions, i.e., scanning step and lateral sensor distance have to conform to the TMS model. The scanning step has to be an integer multiple of the lateral sensor distance. As a rough estimate, a relative error in one of these quantities introduces a relative error of the same magnitude into the measured topography.
- Parallel adjustment, i.e., the scanning direction and the direction of the sensor lines have to be parallel. The adjustment of the sensor has to be tested with a structured object.
- Retrace errors, i.e., for an interferometer a nonvanishing number of fringes corresponds to a deviation from the common-path principle. Consequently, the sensor offsets can be different for different local topographies on the specimen's surface. This would violate the assumptions of the TMS model.[8]
- Strongly-curved surfaces, i.e., the effect of curvature and large slopes on the sensor system has to be characterized and its impact on the calculated specimen topography has to be determined.

6 Conclusion

For the measurement of the form of optical surfaces the new TMS system has been presented. It uses coupled multiple distance sensors, which are scanned along the surface under test. By using a small sensor head a high lateral resolution can be achieved. In addition to the multiple distance sensors, TMS utilizes an autocollimator measuring the tilt of the sensor head, which makes it possible to eliminate systematic errors of the distance sensors. In this way, the TMS system allows high-accuracy measurements of flat and curved surfaces with high lateral resolution. A demonstrator setup was shown and test measurements were presented confirming the high potential of the TMS method.

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