Final Publishable JRP Summary for IND10 Form
Optical and tactile metrology for absolute form characterisation

Overview

The absolute form measurement of optical components, ranging from flat surfaces to aspheres and free form surfaces, was significantly improved by this project. Tactile, optical and capacitive methods, marker production and mathematical methods were developed further. The project strengthens Europe's position in the global photonics market and leads to better optical components and systems, which can be manufactured with less energy and waste.

Need for the project

Optics and the optical industry are among Europe's strengths, but optical surfaces can only be manufactured as well as they can be measured. Thus, while advanced techniques for polishing optics enable removal of material from surfaces at the nanometre level, it is not productive if the deviation to the design form cannot be determined exactly enough. This is demanding for flat surfaces and even more challenging for new aspherical elements with complex forms used in modern optical systems. A surface that is a modified sphere and still has rotational symmetry is typically denominated as an "asphere". Even if the rotational symmetry is lost, the surface is described as a "free form surface", but often "asphere" is used for both categories.

Aspheres are found in almost every optical system from intraocular lenses used to treat cataracts, glasses, cell phone cameras, consumer and high-end cameras, to astronomical and photolithographic systems for computer chip production.

The high potential of European optics and metrology systems manufacturers urgently needed more accurate form measurement and improved asphere standards traced back to National Metrology Institutes (NMIs). The accuracy that is needed ranges down to a few tens of nanometres. For high-accuracy instruments existing at NMIs, in industry and institutes, absolute accuracy estimations, cross checks and comparisons are necessary. These are supported by suitable reference surfaces. Improvements and new developments of high-accuracy measuring instruments foster these capabilities.

Scientific and technical objectives

The scientific and technical objectives for this project were:

1. **Flatness metrology**
   - To achieve measurement uncertainties of 1 nm (peak-to-valley) or 0.25 nm root mean squared (RMS) for nearly flat surfaces (peak-to-valley less than 1 µm).
   - To develop a new technique of flat surface measurements based on capacitive distance-sensors with an uncertainty of 10 nm or better; and
   - To attain at least a 10-fold improvement (to less than 0.1 mm) in the lateral resolution in flatness measurements.
2. **Optical imaging metrology for curved surfaces**
   - To realise a sub-aperture tilted-wave interferometer for absolute form measurement of aspheres and freeform surfaces (diameter up to 200 mm) with uncertainties of a few 10 nm and the capability to measure specimens with maximum slope angles of 10° and a lateral resolution down to 10 µm.
3. **Tactile and optical single point metrology for curved surfaces**
   - To demonstrate an improved form measurement accuracy of <50 nm for optical surfaces using tactile and optical single-sensor scanning methods by investigating error influences using virtual

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CMM modelling (task-dependent for complex form parameters) with local slope angles of at least 50° for tactile and 15° for optical-measurements.

- To realise tactile measurements for absolute form measurements of optical aspheres and freeform surfaces (diameter 1 mm to 80 mm, maximum slope angles of 90°) with uncertainties of a few 10 nm.

4. **Data analysis**
   - To realise algorithms and software to reconstruct surface topography and derive topography parameters and associated uncertainties from a large number (some 10^5 to 10^6) of individual data points taking into account instrument parameters and uncertainties.
   - To realise procedures to make possible quantitative comparison of surface topographies measured with different instruments considering specimen properties (form and waviness) and instrument properties (lateral resolution, data grid and uncertainty).

5. **Reference standards**
   - To develop standards (including aspheres) applicable for calibration and characterisation of surface form measuring instruments for optical surfaces.

Results

Objective 1: Flatness metrology

Measurement uncertainties for nearly flat surfaces

For flatness measurement with extremely low uncertainties, small angle deflectometers can be used. These are instruments using autocollimators (detecting the local surface angle) combined with a 90° beam deflecting unit (e.g. pentaprism) to scan the surface under test.

PTB's deflectometer was analysed and uncertainty estimations for different specimen sizes were performed. For the deflectometer, an uncertainty of 0.25 nm (RMS, k=1) resulted for a scan length of 120 mm. For larger scan lengths this value increased. Additionally, the calibration of autocollimators, necessary for these types of measurements, was developed further.

A comparison of PTB's deflectometer with the deflectometer used at the Helmholtz-Zentrum Berlin supported the uncertainty estimation because a comparison of both systems showed a deviation of less than 0.5 nm for a scan length of 500 mm [30].

Flat surface measurements based on capacitive distance-sensors

The flatness measurement technique based on capacitive distance-sensors was successfully developed [16] and an expanded uncertainty of 5.4 nm, well below the target of 10 nm, was achieved. The system compared the surface under test to a reference surface. Both surfaces had to be slightly coated (electrically conducting) to allow for the capacitive measurements. The components of the setup are much less expensive than optical interferometers and thus a low cost flatness metrology solution for small and medium sized companies with nanometre uncertainty is now available. The optical flat referencing can also be used for testing high-accuracy motion systems.

Improvement in the lateral resolution in flatness measurements

The measurement technique for nearly flat surfaces described above typically uses beam diameters of some millimetres. In the project, a more than 10-fold improvement in the lateral resolution in flatness measurements was reached. The scanning spot could be reduced to 0.2 mm for a circular aperture and down to 50 µm for a slit aperture [31]. Thus, the spatial resolution possible in deflectometric flatness measurements was largely increased beyond the state of the art.

For small scanning spots, the Exact Autocollimation Deflectometric Scanning principle [3], and in particular the scanning autocollimator acting as a Null detector was further developed.

Objective 2: Optical imaging metrology for curved surfaces

Tilted-Wave Interferometry

Developing, applying and analysing an asphere interferometer with the full knowledge of all hard- and software components was jointly realised in the project by PTB, Mahr and UST. The basic principle of the interferometer, invented by UST, is called Tilted-Wave Interferometry because the specimen is illuminated by several wavefronts, which come from different point sources, and result in differently tilted wavefronts.

As first step, the full aperture Tilted-Wave Interferometer (TWI) was realised as a physical metrological prototype with an objective with 48 mm focal length and modelled equivalently in a simulation environment. The differently tilted waves from the light sources array used for illumination allowed for measurement of local aspherical deviations of more than 10° in surface angle (with respect to the best fit sphere). For small and strongly curved specimen the lateral resolution reaches down to about 10 µm.

In a next step, a variable objective for specimen with larger radii was designed and acquired. The focal lengths can be adjusted to 120 mm, 175 mm and 255 mm.

A linear stitching-software was developed to combine data from the different sub-apertures; and the use of this instrument in sub-aperture stitching was analysed in the simulation environment and an uncertainty of a few 10 nm was estimated (λ/5 PV or λ/25 RMS for diameters up to 200 mm).

Finally, a full 3D scanning and stitching procedure was developed, which can be used for evaluating the stitching measurements for a complete specimen surface.

Mahr, as a metrology instrumentation manufacturer, will bring such an instrument to market. Mahr and UST have already cooperated on the development of the interferometer in a previous project, but the developments of this project are adding significant additional quality because PTB will be able to robustly estimate the uncertainty. At PTB, a prototype of the TWI was set up in cooperation between the partners and was optimised for uncertainty reduction. It has also been extended with an environment control system, including temperature sensors inside the instrument. In parallel, Mahr is bringing a version suitable for industrial customers to the market (fast, optimised for user-friendliness, etc.).

Objective 3: Tactile and optical single point metrology for curved surfaces

Improved form measurement accuracy for optical surfaces

The optical imaging interferometer, presented above, was complemented by the various single point measuring principles. The ultra-high precision single point form measuring machines of the NMIs (LNE, VSL, SMD and METAS) and the industrial partners (TNO and IBSPE)) were improved in accuracy by investigating and consequently reducing or eliminating error influences [21].

These machines are equipped with tactile or optical single point scanning probes with sub-nanometric resolution. Since their probing errors can be characterised separately from the machine geometric errors, their behaviour was investigated. The results obtained revealed that the probes do not present similar types of behaviours, but are highly repeatable. The information was used to compensate for the machines' errors and improve their measuring capabilities.

Task specific uncertainty modules based on numerical modelling were developed and implemented for the measuring instruments at VSL, METAS and TNO. With this tool, not only the uncertainty for a specific specimen can be estimated, but moreover, an uncertainty can be associated to each parameter of the asphere. For these measuring machines (using tactile and optical single-sensor scanning, respectively) an improvement of the single-point form measurement accuracy to <50 nm for optical surfaces was demonstrated as an example.

Tactile measurements for absolute form measurements of optical aspheres and freeform surfaces

For the tactile instruments, absolute form measurements of optical aspheres and freeform surfaces (diameter 1 mm to 80 mm, maximum slope angles of 90°), with uncertainties of a few 10 nm, were realised by investigating and reducing static, as well as the dynamic effects.

The investigation of probe surface interactions during the probing revealed several critical parameters that influence the onset of plastic deformation of the material being measured and the probe: mechanical properties of the materials, mass of the probing system, probing speed, and elastic constant of the suspension. For the ultra-precise systems, the static probing force was below the onset of plastic deformation for most materials of optical surfaces.

The dynamic forces played a more important role and it was found that the mass of the probe, the probing/impact speed and the elastic constant of the suspension should be kept as small as possible. This was within the possibilities of the machines used in the consortium. For soft materials care was needed to set the probing/impact speed low enough.

At CMI, an experimental setup for the measurement of probing deformations with a resolution of 10 nm was designed and assembled enabling further investigation of the mechanical effects.

Objective 4: Data analysis

Algorithms and software for surface topography reconstruction

The different measuring instruments, i.e. the imaging and single-sensor optical and tactile systems, deliver topographical data that differ due to differences of the lateral resolution and the measurement grid of the systems. Detailed knowledge of the implications of these effects on measured topography data was developed [18]. Furthermore, the measurement systems generate large data sets; the amount of data can be as high as 10^6 individual data points. Based on this knowledge, different algorithms were realised in software and tested on data from the comparison measurements with the different measuring machines in the project.

Procedures for quantitative comparison of surface topographies

It is also of major importance to quantitatively compare data from the same test sample measured with different instruments and thus it was necessary to validate different form measuring instruments. When measurements are performed and the data recorded, the surface form should be evaluated by fitting the appropriate model to the measured data with nanometre accuracy. The project developed procedures to make quantitative comparison of surface topographies possible when measured with different instruments and when considering specimen properties (form and waviness) and instrument properties (lateral resolution, data grid and uncertainty). Two comparisons were conducted on the participants' instruments (some of them are commercially available instruments, others NMI designed or modified), which revealed differences between the instruments and from which the instruments could be further improved.

Objective 5: Reference standards and marker structures

Standards for calibration and characterisation of surface form measuring instruments

Reference standard surfaces for transferring traceability in asphere metrology are the final link to industry. Whilst conventional aspheres (as applied in real optical systems) can be used, metrological aspheres (i.e. surfaces that do not necessarily make sense in real optical systems, but reveal properties that are suitable to detect particular errors) have been developed within the project and will be made available for instrument users and manufacturers. They are of high importance for the calibration and characterisation of surface form measuring instruments for optical surfaces.

Because these form standards are not completely rotationally symmetric, they need to have easily detectable structures for lateral positioning. Hence marker structures are important and have been developed within the project by TU-IL. The challenging task was to develop, produce and measure marker structures on curved optical surfaces; and these markers are enabling the referencing of the coordinate system from measured topography data with high precision.

Actual and potential impact

The metrological capabilities for the form measurement of aspheres (and freeform surfaces) as used in optical systems have been improved significantly:

- Flatness metrology has been improved by further developing small angle deflectometric principles. Regarding uncertainty, the level of 1 nm peak to valley was reached and regarding resolution, a level below 0.1 µm was attained.

- An asphere interferometer has been realised at a NMI with the knowledge of the complete system. Thus uncertainty can be completely understood and estimated.
- The highest accuracy optical and tactile single point scanning instruments at the NMIs, institutes and in industry have been improved and task specific uncertainty estimations have been realised.
- Some NMIs can now offer traceable calibration services for aspheres with fix or fitting parameters.
- An absolute uncertainty of the form measurement of less than 50 nm has been realised.
- Data analysis appropriate for aspheres has been developed.
- Reference surfaces suitable for reducing uncertainty have been developed as have marker structures suitable for curved surfaces.

The results of the project have also been widely disseminated. Within the project lifetime about 30 high impact publications in key journals have been generated (see below) in cooperation between the partners. These incorporate the significant scientific outputs of the project.

- The work carried out in the project was presented at various conferences, seminars and other meetings and more than 60 presentations have been given by the partners in Europe (Germany, Netherlands, United Kingdom, Spain, France, Croatia, Austria and Hungary) and outside Europe (USA, South Africa, Taiwan/China). A keynote presentation was given at the European Optical Society conference at the World of Photonics Congress 2013 - Testing for Fabrication and Assembly.
- Four trade journal articles were published to make the project known to a broader audience. The project and its results were presented at several trade shows and company booth presentations at several conferences.
- Together, seven workshops and training modules were performed by the partners during the project for the project partners and external partners.
- Applications for four patents have also been submitted during the project lifetime.

The outputs of the project are already being used. An example of an early impact is the contribution of Mahr as the manufacturer of an instrument based on TWI interferometry. The instrument developed within this project is a first prototype of a commercial instrument. Mahr performed a market study, which found that worldwide over 100 companies exist that produce aspheric lenses made of glass, with a strongly growing trend. There will be a worldwide demand for very many interferometers based on the TWI principle. This asphere interferometer will be the only one that is traced back in cooperation with an NMI and thus it will be a unique instrument on the market with a high importance for all manufacturers of optical surfaces.

The possibility of the implementation of marker structures on optical surfaces (and the algorithms and software developed in project) will enable precise data comparison or data fusion of topography measurements stemming from various technologies. This will lead to the reduction of the uncertainty of measurement systems in general.

During the project, an intense exchange with the participants of the High Level Expert Meetings of the Competence Centre for ultra-precise surface manufacturing (CC-UPOB), which is a worldwide forum for asphere metrology, was established and will also in future be used for generating impact. The first measurement requests on aspherical surfaces from industrial customers are being processed by PTB.

List of publications

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