Publishable Summary for 20IND07 TracOptic
Traceable industrial 3D roughness and dimensional measurement using optical 3D microscopy and optical distance sensors

Overview

To remain competitive, European manufacturers strive to make constant improvements in their manufacturing processes. The surface topography of a component part can have a profound effect on the function of the part. This is true across a wide range of industries (such as precision engineering, automotive, and medical). It is estimated that surface effects cause 10% of manufactured parts to fail, which has financial implications. Optical measuring systems are widespread in surface and coordinate metrology as they are fast, with high resolution, and contactless (aspects that are essential for the factory of the future). Unfortunately, optical measurements are not often used in industry as they are not traceable. This is due to the complexity of the interaction between the object's surface and the measuring system. This project aims to improve the traceability of 3D roughness and dimensional measurements using optical 3D microscopy and optical distance sensors. Data evaluation, and uncertainty estimation methods will be developed and made accessible to industry through good practice guides, publications, and training courses.

Need

For European industry to remain competitive, improvements to inline measurements in manufacturing processes across a wide range of industries are required. Optical microscopes and optical distance sensors have become indispensable in manufacturing processes. The possibility to integrate these into production lines enables fast and non-destructive measurements, and fast data evaluation accelerates the evolution of Industry 4.0. The European dimensional metrology market generated revenues of $1.11 billion in 2017 and was estimated to continue growing by 6 % (CAGR, Compound Annual Growth Rate) until 2022.

The EURAMET comparison measurement #1242 on areal roughness measurements by optical microscopes has revealed discrepancies in roughness values (e.g., Sa (arithmetical mean height) and Sq (Root mean square height)), which strongly depend on the measurement principles. For example, the deviation of Sq can reach 85% for Sq ~ 50 – 60 nm and 60% for Sq ~ 100 nm. Moreover, the measured parameters also depend on the optical instrument's setup, the chosen analysis strategy, and the feature geometries of the surfaces, i.e., amplitudes, spatial frequencies, slopes, and curvatures. Each of these is critical to understanding if a given instrument can reliably, accurately, and traceably measure a certain roughness. Yet, end users (e.g., precision engineering and automotive manufacturers) have little guidance on the selection of a suitable instrument (and align the settings) to measure roughness accurately and traceably. As a result, often, tactile measurements are carried out. These are traceable but much more time consuming and costly.

Dimensional measurements with optical distance sensors are also strongly influenced by the surface and geometrical characteristics of the measured object (in particular roughness, form, and slope). This results in a significant deviation in the determined geometrical measurands, and it limits traceable optical measurements of dimensions. This influence is not considered in acceptance and reverification testing according to ISO 10360. Moreover, only optical cooperative reference standards are used for the tests. Therefore, the specifications in the data sheets are of limited value for the selection of the appropriate sensor for a specific measurement task.

Objectives

The overall objective of the project is to enable traceable areal roughness and dimensional measurements using optical 3D microscopy and optical distance sensors, with special emphasis on giving guidance for selection of most suitable instrumentation for a particular purpose. The specific objectives are

1. To determine suitable surface texture parameters and, in some cases, dimensional properties of different types of samples: (i) available well-known roughness standards (profile and areal, coarse to superfine roughness (Sa from several µm down to several nm) (ii) typical technical surfaces made by turning, milling, grinding, polishing, lapping or spark-erosion and roughness samples produced by new manufacturing technologies (e.g. FIB, lithography, and additive manufacturing); (iii) spheres with different surface characteristics and (iv) solid roughness samples from biology and medicine.
2. To characterise the measurement capabilities of 3D optical microscopy, AMI interferometric nanoscopy and optical distance sensors, including (i) measurable local slope distribution, (ii) bandwidth by power spectral density (PSD) (iii) measurement noise, (iv) influence of the bidirectional reflectance distribution function (v) topography fidelity and structural resolution and (vi) length error for distance measurements. Additionally, to investigate the influence of (i) measurement principle, (ii) hardware setup, (iii) feature geometries (e.g. amplitude, spatial frequency, slope distribution, curvature) and (iv) software on areal roughness and dimensional measurements.
3. To develop numerical models to predict the sensor response for any complex surface geometry, and to allow such models to be used for systematic error analysis based on analytical models or computation models using rigours 3D Maxwell solvers for solving the light matter interaction (e.g. Fourier modal methods, Rigorous coupled-wave analysis (RCWA) methods, finite element (FE), or boundary element (BE) methods). This will include the development of approaches for the correlation between roughness and dimensional parameters and the PSD, topography fidelity and slope distribution. Additionally, to evaluate the performance of a systematic error analysis and error correction.
4. To develop and validate procedures for the selection of appropriate instrumentation for a given measurand. The target uncertainties are 5 nm (10 % deviation for 50 nm < Sq < 100 nm) for optical roughness measurements and 100 nm for optical dimensional measurements. This will include the development of methods for data evaluation and simplified uncertainty estimation.
5. To facilitate the take up of the technology, measurement infrastructure and good practice guides developed in the project by the measurement supply chain, standards developing organisations (e.g. ISO TC 213 WG10 and WG16) and end users (in the fields of optical, semiconductor, automotive and mechanical engineering).

Progress beyond the state of the art

The project has for the first time developed a systematic classification of different types of samples beyond conventional roughness artefacts and conventional artefacts for testing of coordinate measuring systems such as newly developed areal roughness standards used in EURAMET comparison #1242, or fabricated by FIB, or new lithography methods in advanced manufacturing. Beyond the height parameters, the spatial wavelength range, the local slopes and curvatures, and the BRDF properties of the artefacts have been determined.

In order to characterise the measurement capabilities of 3D optical microscopy and optical distance sensors, the characteristics of the instruments in dependence on the workpiece characteristics were investigated using appropriate reference standards. With sinusoidal chirp standards developed at PTB and TUK, rectangular resolution standards from SiMetrics and spheres the topographic spatial resolution, topography fidelity, structural resolution, and maximum measurable slope of the four types of instruments have been characterized. Evaluation methods have been discussed and further developed, algorithms for PSD calculation are validated and provided to the consortium.

To develop numerical models to predict the sensor response for any complex surface geometry and to allow such models to be used for systematic error analysis, approximate and rigorous methods are used to model light scattering and diffraction by a surface. The conditions for validity for these models have been defined in this project, as this has not yet been achieved.

Universal theoretical platforms are under development that allow prediction of an optical instrument response from any complex surface geometry and allow such platforms to be used in uncertainty evaluation.

Virtual instruments of four typical optical instruments, CM (confocal microscopy), CSI (coherence scanning interferometry), FV (focus variation microscopy), and ODS (optical distance sensors), are under development and will be verified by comparison with real instruments. Systematic deviations, correlation between lateral resolution (topography fidelity, structural resolution), PSD and roughness, and dimensional parameters will be investigated using the virtual instrument models.

The project will go beyond the state of the art by delivering Good Practice Guides with validated procedures for the selection of appropriate instrumentation for measuring roughness and dimension. These guides will cover four different measuring principles, setups, data analysis, including stitching, and simplified uncertainty estimation.

Results

Determination of suitable surface texture parameters of different types of samples

Different types of samples, including spheres, chirp structures, RS-M and RS-N, ARS samples, typical surfaces fabricated by conventional and new advanced manufacturing methods (e.g., additive manufacturing, focused ion beam), and human teeth have been selected or developed.

Relevant surface texture parameters, dimensional parameters and BRDF parameters characterized by AFM, tactile instruments, or gonioreflectometers have been determined and collected. In addition, the slope distribution and the power spectral density of the AFM or tactile measured surfaces have been characterized which are important properties for the selection of appropriate instrumentation.

From the list of available samples, the most suitable samples have been selected for comparison measurements within four groups of optical instruments, i.e., CSI, CM, FV, and ODS. These include calibration standards (optical flats, silicon lapped areal roughness standards, spheres, chirp structures, rectangular gratings, ball bars, ball plates, micro-contours, BRDF samples), and some samples (e.g., plastic blocks) from stakeholders.

Characterisation of the measurement capabilities of 3D optical microscopy and optical distance sensors

The maximum measurable slope, measurement noise, and PSD, the influence of the bidirectional reflectance distribution function, topographic spatial resolution/structural resolution and topography fidelity, and the length error for distance measurements of the four kinds of instruments have been characterized using the selected calibration standards and samples.

Sample circulations are completed, and the measurements have been carried out according to the previously prepared technical protocols for different measurement instrumentation groups which were distributed within the consortium. Also, a technical protocol for the machined technical surfaces from a stakeholder was developed and currently the partners are performing measurements.

The data collection, distribution and processing plan was conducted. PSD results have been compared with different software and different algorithms. A uniform algorithm (realized in Matlab and python) was provided to the partners. Some measurements (e.g. Chirp) have been evaluated and summarized by the pilots centrally. Other measurements are analysed by partners themselves and the four instrument types results have been summarized by the appointed partner (analyst). Deliverables D2, D3 and D4 summarizing the results achieved with the different instrument groups are drafted.

Development of numerical models

Different scattering models have been developed, including approximate and rigorous models. The intensity of the near-electric field scattered from a single cylinder and a sinusoid is obtained by four rigorous models including the boundary element method (two approaches), finite element method and the Fourier modal method. The results are compared with the Mie solution as a reference method for the single cylinder. The accuracy of the results along with the advantages and drawbacks of each model are discussed in a draft of a research paper.

Virtual instruments have been developed including virtual CSIs, which are based on the foil model of the surface and linear theory of 3D imaging, combining Fourier optics modelling and the 3D transfer function of the CSI instrument (UFO), Elementary Fourier Optics (EFO) respectively, one virtual CM model, based on Fourier wave propagation, one chromatic confocal ODS model and two virtual FV models, which are based on the ray tracing method. Some numerical calculations based on simulated objects or measured surfaces have been performed and compared with each other to verify the virtual instruments.

The use of the virtual instrument to evaluate the measurement uncertainty is underway and a couple of test samples and surfaces including sinusoidal pseudo-chirps with different amplitudes, resolution standards with various height and pitch values, spheres with different diameters and roughness standards will be used for the uncertainty evaluation by comparing surface topographies obtained by virtual and real instruments.

Development and validation of procedures for the selection of appropriate instrumentation for a given measurand

First versions of the selection tables for roughness measurements and for dimensional measurements have been drafted and are being discussed between partners.

Different approaches based on stage coordinates and cross correlation to obtain image stitching have been studied. The accuracy of stitching algorithms and the influences of different input parameters (overlaps of different areas, errors of positioning systems, topography) are simulated, and Monte Carlo simulation proved to be feasible to evaluate the stitching uncertainty. Another stitching and data evaluation method using different features like the displacement system, geometric features, graph features, Gaussian mixture model features, or deep learning features has been investigated as well.

The activity on the evaluation of a complete uncertainty budget containing the contributions for the surface roughness and for dimensional measurements is ongoing. The aim is to rank the different contributions in order to select the major and minor contributions and obtain a simplified model of uncertainty budget.

Impact

To promote the uptake of project results and to share insights generated throughout the project, results were shared broadly with scientific and industrial end-users. Five papers reporting project results have been published in peer-reviewed journals (e.g., Optical Engineering, Metrology), and five articles were published in conference proceedings (e.g. Applied Optical Metrology and EOSAM 2022). Thirty-three presentations have been given at national and international conferences and workshops (e.g., Wiley Analytical Science, SPIE Optical Engineering, SPIE Photonics Europe, VirtMet, Euspen ICE 2023 and NanoScale 2023). In addition, the project has been presented at national and international standardization committees (DIN, ISO, METSTA, AENOR, VDI/VDE) and at EURAMET TC-L. Furthermore, eight training activities (for example “3D micro- and nano-structures: fabrication and measurement” and “Ultra-high precision metrology for form and texture) have been carried out. Annual stakeholder committee meetings and annual stakeholder meetings are held to update stakeholders on project progress and to receive valuable stakeholder feedback.

Impact on industrial and other user communities

The methods, metrology, and Good Practice Guides developed within the framework of this project will lead to a better reliability for the fast and non-destructive control of surface quality and geometry for the optical, semiconductor, automotive industries, precision mechanical engineering, advanced manufacturing industry (including workpieces fabricated with new manufacturing technologies such as additive manufacturing, laser manufacturing, and FIB), medical industries, biotechnology, metrology service providers, and precision investment casting, and consequently will accelerate the evolution of industry 4.0 and the Key Enabling Technologies (KETs).

The manufacturers of optical measuring instruments will strengthen their position in the global market and secure jobs. The speed and non-destructive working principle of optical measuring methods will be a huge advantage that will be exploited and strengthened.

The needs of industrial users will be clarified and fed into the project through the Stakeholder Committee (SC), and the feedback from the SC will be collected for the development of good practice guides. Corresponding guidelines for industrial users and end-users from various disciplines on which instrument setup should be used for traceable measurements within a specified uncertainty range will be available on the project website and as publications. The technologies developed during the project will be transferred to industry and cross-disciplinary end-users through training courses/workshops, collaborations, and case studies.

Several training courses and workshops have been offered to industrial and scientific communities on topics such as 3D micro- and nano-structures fabrication and measurement, Advanced Focus Variation and Ultra-high precision metrology for form and texture. A presentation on Roughness was made to Italian industry at a meeting hosted by the CMM Club.

Several visits to industry have also been made to discuss industrial needs and present project progress.

Impact on the metrology and scientific communities

Metrology impact: A broad range of end users will profit from the project’s outcomes, including the ability to select the appropriate sensor and settings to obtain traceable measurement results. This will reduce measurement uncertainties and costs. In addition, calibration laboratories, NMIs, research institutes, and universities will also benefit from the results due to the possibility of offering services for traceable 3D roughness and dimensional measurements as well as traceable reference materials.

Scientific impact: This project provides a significant step forward in traceable dimensional and roughness measurements with optical measuring systems. This leads to a deeper understanding of the relation between topography features, sensor characteristics and measurement results and reduce uncertainty. The developed measurement methods have been presented at some international conferences and/or submitted to open access, peer-reviewed journals during the project. Good practice guides will be made available toward the end of the project on the project website and in institutes' newsletters; the achieved output of the project will be discussed at stakeholder meetings; and it will be advertised through workshops, symposia or special sessions at international or European conferences.

A special TracOptic session was held at the SPIE Conference on Optical Metrology 2023 with 8 presentations and one poster on project progress. Two stakeholder committee meetings have been held and stakeholders are invited to the trainings and workshops offered by the project.

The project was represented at the trade fair A&T-Automation & Testing 2023 which was held in Italy.

Partners have been interacting with various scientific, metrological, and industrial networks such as VDI/VDE, DGaO, European Optical Society to present the preliminary results.

Impact on relevant standards

The consortium has participated in several committee meetings and presented the work of TracOptic partners, such as ISO/TC 213/WG 16 Areal and Profile Surface Texture, METSTA TC K290, AENOR UNE CTN82/SC Dimensional Metrology, DIN NA 062-08-02 AA Test Methods, VDI/VDE-GMA Technical Committee 3.41 Surface Measurement Technology in Micro- and Nanometer range and VDI/VDE-GMA Technical Committee 3.31 together with DIN NA 152-03-02-12 GUA KMT Coordinate Measuring Machines.

The metrological outputs in the fields of surface metrology have been presented to ISO/TC 213/WG16 to advance the development of corresponding standards in the 25178-70x series and transferred to the national level such as DIN NA 152-03-03, UNM 10 GPS, METSTA TC K290, UNI CT047 GL Superfici. Guidelines for the calibration of CSI and CM will be further developed or revised in the German VDI/VDE-GMA Technical Committee 3.41. In the field of dimensional metrology, the results will be presented to ISO/TC 213/WG 10 Coordinate Metrology in March 2024 for the further development of the standard ISO 10360-8. The guidelines for the application of ISO 10360-8 will be further developed in the German Technical Committee VDI/VDE-GMA 4.31 / DIN/NA 152-03-02-12 GUA KMT Coordinate Measuring Machines. In addition, the results of this project will be disseminated through discussions and presentations at meetings of the EURAMET TC Length. Feedback on the presented results will be sought.

Longer-term economic, social and environmental impacts

Improved optical measurements will lead to an increased use in industry and this will save time and costs as well as improve the competitiveness of European industry. Providing the European manufacturing industry with a strong tool such as traceable optical measurements, will help the industry to keep their production in Europe and to reduce the amount of outsourcing to, for example Asia. The research will accelerate the evolution of industry 4.0 and the Key Enabling Technologies (KETs) by fast and traceable measurements enabling non-destructive 100 % control of manufactured surfaces and geometries. Moreover, it will support innovative designs because of better measurement capabilities for geometrical and surface roughness specifications of components with smaller tolerances.

Any European enterprises which require measurements of complex parts will benefit from the project results as their manufacturing costs will be reduced and their market penetration will increase. The manufacturers of optical measuring instruments will strengthen their position in the world market and secure jobs on a sustained basis. Reliable precision parts further result in improved, long-lasting technical solutions.

The increased use of optical sensors will speed up product development and production processes, and it will reduce the energy used in the manufacture of physical prototypes. The use of traceable optical measurements in quality assurance and quality control will result in the earlier detection of scrap parts, increasing the possibility to reuse materials and components as well as reducing waste.

List of publications

1. De Groot, P., et al. Modelling of coherence scanning interferometry using classical Fourier optics, *Optical Engineering, 60(10), 104106 (2021)*. https://doi.org/10.1117/1.OE.60.10.104106
2. De Groot, P., et al. Fourier optics modelling of coherence scanning interferometers, Proceedings Vol. 11817, Applied Optical Metrology IV, 11817OM (2021) https://repository.lboro.ac.uk/articles/conference_contribution/Fourier_optics_modelling_of_coherence_scanning_interferometers/16948690
3. Schaude, J., et al. Effect of a Misidentified Centre of a Type ASG Material Measure on the Determined Topographic Spatial Resolution of an Optical Point Sensor, Metrology, 2(1), 19-32 (2022). https://doi.org/10.3390/metrology2010002
4. Lehmann, P., et al. Three-dimensional Transfer Functions of Interference Microscopes, Metrology 2021, 1(2), 122-141 (2021). https://doi.org/10.3390/metrology1020009
5. Fu, L., et al. Simulation of realistic speckle fields by using surface integral equation and multi-level fast multipole method, Optics and Lasers in Engineering, Vol. 162, (2023). https://doi.org/10.1016/j.optlaseng.2022.107438
6. Hansen, P.-E., et al. A virtual microscope for simulation of nanostructures, EPJ Web of Conferences 266, 10004 (2022). https://doi.org/10.1051/epjconf/202226610004
7. Ma, Z., et.al. Harvey-Shack theory for converging-diverging Gaussian beam, JOSA B, (2023). https://doi.org/10.1364/JOSAB.478801
8. Paredes, J., et al. Towards task-specific uncertainty assessment for imaging confocal microscopes, Proceedings Euspen ICE 2023 (2023), https://www.euspen.eu/knowledge-base/ICE23191.pdf
9. Hooshmand, H., et. al. Comparison of coherence scanning interferometry, focus variation and confocal microscopy for surface topography measurement, Proceedings Euspen 2023 (2023) https://www.euspen.eu/knowledge-base/ICE23170.pdf

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2021, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Uwe Brand, PTB   Tel: +49 531 592 5100   E-mail: Uwe-Brand@ptb.de
Project website address: https://www.ptb.de/empir2020/tracoptic/home/</td></tr>
<tr><td>Internal Funded Partners:
1. PTB, Germany
2. CEM, Spain
3. DFM, Denmark
4. GUM, Poland
5. INRIM, Italy
6. LNE, France
7. RISE, Sweden
8. VSL, Netherlands
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15. TU-Ch, Germany
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