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Development of a Chromatic Confocal Sensor Model Dedicated to Investigating Object-Dependent Effects

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Summary:
In optical dimensional metrology object-dependent systematic effects significantly influence measurements and limit traceability. With the aim to describe and if possible correct systematic effects and estimate task-specific measurement uncertainties, PTB developed a virtual instrument that allows to consider the influence of the specimen. Early simulations show such effects.

Keywords: digital twin, chromatic confocal sensor, ray tracing, traceability, optical metrology

Introduction

The benefits of optical metrology are in demand from many different industries. However, optical dimensional and 3D roughness measurements still suffer from limited traceability causing a lack of confidence in their results and therefore preventing an even wider application.

A great challenge is the complexity of the light-matter-interaction. Although the physics accurately describes the scattering of light, it might either be too computationally expensive, or not all constraints regarding the measured surface are known. Additionally, the resulting systematic effects strongly depend on the applied instrument – there are not only fundamental differences among the many measuring principles but even among instruments of the same batch significant differences can occur, e.g., because of small differences in the adjustments of the respective imaging systems.

In order to approach this topic, PTB has initiated the joint research project TracOptic. Characterizing multiple confocal microscopes, coherence scanning interferometers, focus variation microscopes and optical distance sensors regarding workpiece influences, we aim to set up virtual instruments capable to correct or predict systematic effects. Hence, we will be able to use those models to estimate task-specific measurement uncertainties.

In this article we will present our approach to model a commercial chromatic confocal probe (CFP) [1], describe early implementations and show early simulation results.

General Description of the Virtual Instrument

We are using the SimOptDevice-Toolbox [2] which is an in-house development of PTB to model optical experiments to simulate the light propagation based on geometrical optic theory, i.e., ray tracing. It provides us full accessibility to all algorithms and has already proven itself in various other use cases [3].

A software-package dedicated to model all aspects of the measurement system relevant to us had been set up recently. It includes the illumination, scattering at the specimen, the detection as well as algorithms for confocal peak evaluation. Also, the axes of the associated CMM are included although our current research focuses on an accurate simulation of single point measurements assuming an ideal CMM.

We reached a state where we can run and present full simulations of measurements of easy to describe surfaces.

As of right now, a major limitation is that only ideal specular and diffuse (Lambertian) reflection are implemented. However, we can already survey first systematic effects introduced by the measured object while measures to simulate more realistic reflection characteristics are currently being developed by partners in TracOptic.

Simulation Results

We expect that the most significant systematic effects are caused by the instrument's response to surface slope, curvature, and reflection characteristic. Therefore, we ran two simulations in which we varied slope and curvature, respectively.

Each simulation returns an intensity distribution over a section of wavelengths – the confocal peak. Such peaks are evaluated using dedicated algorithms to return a single wavelength λ_m describing the location of that peak. The following results were achieved applying a center of gravity algorithm using intensity values of 50 % and more relative to the corresponding maximum value.

As a first case we set up a plane specimen and varied its orientation relative to the instrument's optical axis. Fig. 1 shows in case of a specular reflection a peak to valley deviation of approximately 0.8 nm which – depending on the operating distance – translates to a difference of a height measurement of about 800 nm for the modeled sensor. As expected, there is no significant influence of surface tilt when measuring Lambertian surfaces. However, such measurements might suffer from a reduced SNR when measuring higher slopes which is currently not captured by our model. The results for specular reflection show some mild outliers due to higher slopes causing rays to miss the instruments aperture.

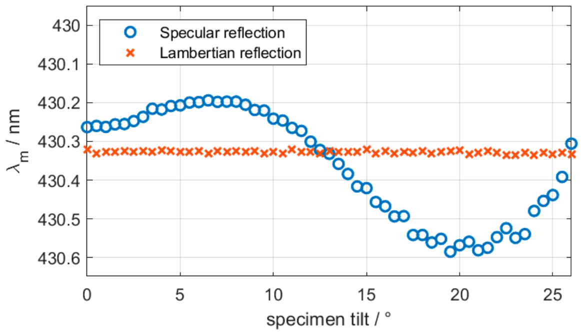

Fig. 1. Simulated focal wavelength λ_m for different surface slopes.

In the second case the measurement of a spherical specimen was simulated (Fig. 2). The radius was varied between 0.1 mm and 1 mm with negative values describing a convex surface and positive values describing a concave surface. The spot-size of the modeled sensor is specified to be 5 µm in diameter. The measured point is located at the pole, so the distance to the sensor remained constant. In addition, the results for a flat sample are represented by an infinite radius of curvature.

Fig. 2 shows a less distinct influence of surface curvature compared to tilt. At least on a macroscopic scale curvature seems to be less significant. However, the results suggest that this effect might cause large errors when smaller radii of curvature are present, e.g., introduced by certain manufacturing techniques or surface defects. The general characteristic matches previous findings regarding self-imaging effect in confocal microscopy [4].

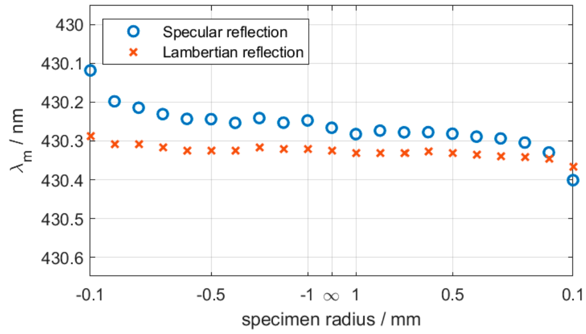

Fig. 2. Simulated focal wavelength λ_m for different surface curvatures.

Summary and Outlook

We have developed a ray-tracing model capable of simulating the measurement process of a CFP. While there is a lot of work to be done, simulations already show that object-dependent measurement errors are significant and need to be addressed to achieve traceable measurements.

Future work will focus on including realistic reflection characteristics, e.g., by introducing BRDF-data (bidirectional reflection distribution function) to our model. Further, we will investigate the influence of diffraction and noise. We will also compare our simulations to measurements in particular to measurements of a specifically designed material standard, we are currently working on.

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