Optical form measurement system using a line-scan interferometer and distance measuring interferometers for run-out compensation of the rotational object stage

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ABSTRACT

Positioning an interferometric sensor with respect to the specimen requires a precise and expensive motion system to retain the sensors accuracy. A cost-efficient and precise setup requires a compensation of any run-out that the motion system induces. This contribution demonstrates that run-outs of a rotational axis can be compensated by implementing a low-cost interferometric point sensor to a previously presented interferometric line-scan system. Furthermore, the setup is extended by an evaluating algorithm that is capable of evaluating the line-sensor's measurement data in real-time, using either a CPU or a GPU. An improved mechanical design of the interferometric sensor is introduced. It consists of fewer mechanical parts compared to previous versions, thus making the sensor more efficient in production and more robust against vibrations. An up-to-date high-speed line camera with a length of 4,000 pixels and line rate of up to 200 kHz increases the measurement rate of the sensor to up to 2,000 height values per second per camera pixel, enabling the sensor to evaluate 8 million height values per second.

Keywords: interferometry, form measurement, run-out compensation, real-time evaluation, phase shifting interferometry

INTRODUCTION

Interferometric systems enable non-destructive measurement of sensitive surfaces with an uncertainty within the nanometer range [1]. However, if extended areas are to be measured with high lateral resolution, precise and expensive motion systems like air-bearing stages are required to retain this uncertainty while positioning the sensor with respect to the specimen to perform sub-aperture measurements. This results in high cost for the motion system and limits the use in industrial applications.

This contribution presents a revision of an already introduced low-cost Michelson interferometric setup employing a line-scan camera and an oscillating reference mirror for optical path length modulation. This results in a sinusoidal phase modulation. Sinusoidal phase shifting has been introduced as a promising alternative compared to linear phase shifting by P. de Groot [2]. The setup is capable of measuring specimens with a diameter of more than 50 mm by stitching ring-shaped sub-apertures using an economic motion system [3, 4]. The measurement system was originally intended to measure form deviations of optical surfaces such as aspherical lenses. Previous results show that the repeatability of this line-scan sensor is in the range of several nanometers [3]. While scanning, the obtained camera pictures are evaluated in real time, using either a central processing unit (CPU) or a graphics processing unit (GPU), reducing the time for evaluation to a minimum. One drawback of this system is that any run-out of the rotational axis that is used to rotate the specimen while scanning results in measurement artifacts. Figure 1 shows that these artifacts impair the measurement results of a surface scan using a cost-efficient axis, requiring them to be compensated.

Therefore, the setup is extended by interferometric point sensors that provide a repeatability of approximately 1 nm [5] to capture systematic and stochastic deviations of the specimen's positioning induced by this axis. The data recorded by these sensors is evaluated and stored in real-time to correct the run-out errors in the measured topography subsequent to the rotational scanning procedure. To demonstrate the feasibility of this procedure, a rotational axis with a mechanically

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flawed bearing is used that induces high mechanical vibration while rotating, resulting in height deviations of the scanned surface profile with a peak-to-peak value of up to ~500 nm. Results without and with the compensation using the point sensor data are presented.

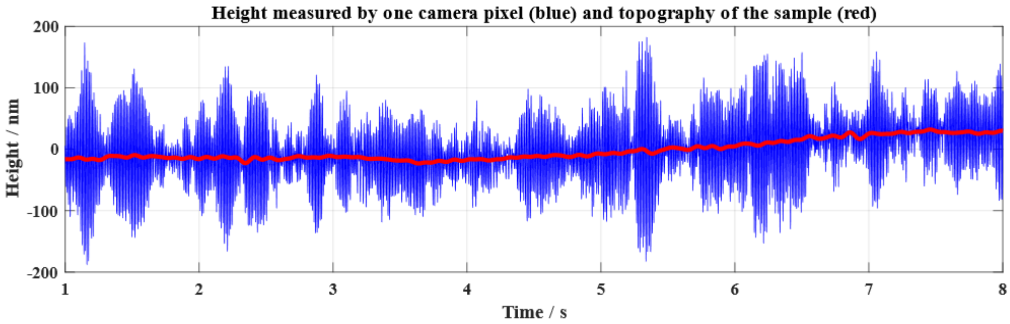

Figure 1: Section of the measured height of a single pixel of the line sensor disturbed by mechanical vibrations (blue) of a cost-efficient mechanical rotation axis while rotating the sample, the red graph shows the topography profile of the sample.

SYSTEM SETUP AND MEASUREMENT PROCEDURE

The experimental setup used throughout this study consists of two interferometric sensors. A low-coherence line scanning interferometer measures extended rotational symmetric objects and a laser interferometer point sensor determines and corrects mechanical perturbations introduced by the rotation stage. The line scanning sensor (Figure 2, left) is based on a Michelson interferometer setup. It uses a 5x microscope objective resulting in an optical resolution of ~2.3 µm (Rayleigh). A beam splitter that is placed in the focused beam of the objective separates the reference and the measurement beam and induces light of the illuminating light source. The light of an externally positioned 50 W Luminus SBR-70-G green LED is guided by an optical fiber into the setup. This LED offers a circular shaped emitting area with a diameter of 3 mm, reducing losses while coupling the light into the fiber. Removing the LED as a heat source from the setup avoids thermal expansion of the mechanical parts increasing the temperature stability, particularly while measuring larger specimens. An optional bandpass filter narrows the width of the LED's spectrum increasing its coherence length and thus the measurement range along the optical axis. A second beam splitter cube couples light of a secondary white-light LED, which enables the sensor to work as a white-light interferometer as well. This white-light measurement mode is used to place the sensor within its working distance perpendicular to the specimen's surface.

A redesigned housing of the sensor (Figure 2, center) offers an improved mechanical mounting for the whole sensor and its optical components. An exchangeable reference path enables to quickly match the reflection properties of the sensor's reference surface to those of the specimen, thus increasing the modulation depth of the interference signal. The currently used flat silicon reference surface is mounted on an immersion coil actuator that modulates the length of the reference arm of the interferometer sinusoidally at a frequency of 1 kHz.

During a measurement, images are taken by an updated Teledyne DALSA Piranha4 line-scan camera at a line-rate of up to 200,000 lines per second (LPS), capturing two spatially separated lines at the same time. If only one line is required, both lines can be binned resulting in an increased sensitivity and a line-rate of up to 100,000 LPS. To avoid sensor heating by the camera's power dissipation (~10 W), the camera is attached to the housing by an insulating 3D printed polylactic acid camera tube. A motorized four-axis motion system moves the sensor with respect to the specimen's surface, three additional manual stages are used for alignment purposes (Figure 2, right). A Physik Instrumente L-611 rotational axis is used as rotational object stage that contains a mechanically flawed bearing. This results in provoked deviations of the specimen's position along the axis of the rotation during movement. These deviations are measured superposed with the specimen's topography obtained by the line sensor and must be compensated during evaluation. To separate these aberrations from the measured height, a fiber-coupled interferometric point sensor as shown in Figure 3 is used. This sensor measures a reference surface simultaneously to the line sensor scan that is influenced by the run-out of the rotation axis as well. The point sensor contains a micro-optical probe head that focuses light of a 1550 nm laser diode onto the reference surface. This probe is mounted on a piezo actuated bending beam. A sinusoidal excitation signal causes the probe to oscillate at a frequency of 1 kHz, thus modulating the optical path length of the measurement path of the interferometer. The sensor measures up to two height values per actuator period with a repeatability of approximately 1 nm [5, 6]. The compensation is demonstrated by measuring a high precision machined specimen with a spherical shaped center surface and a surrounding flat reference surface (Figure 3, right). The point sensor 1 records the axial run-out of this surface and the specimen. A second probe head is located close to the curved shell reference surface and can be used to measure the lateral run-out as well (Figure 3, center). In addition, Figure 2, center shows a configuration where the reference surfaces are separated from the specimen. Thus, arbitrary shaped samples can be measured. In this case, the top surface and the curved shell surface of a high precision cylindrical optical flat are used as reference surfaces.

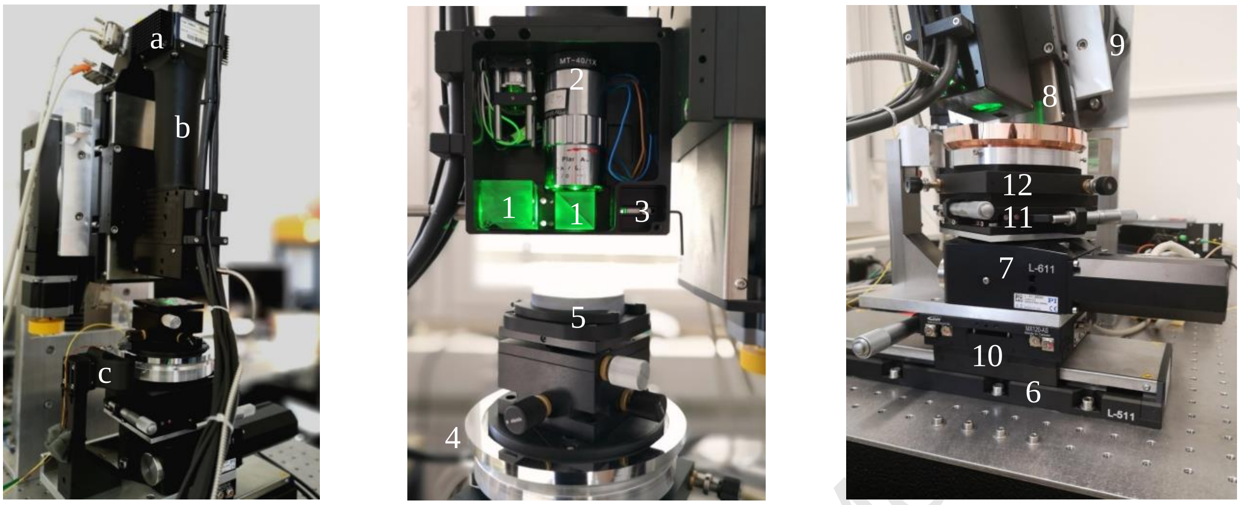

Figure 2: left: measurement setup with line-scan camera (a), camera tube (b) and interferometric point sensor (c);
center: optical setup of the line-scan sensor with two beam-splitters (1), microscope objective with tube lens (2), exchangeable reference path (3), sample mounting with reference surface for the point sensor (4) and calibration sample (5);
right: positioning and alignment system containing four motorized (6 - 9) and three manual stages (10 - 12).

The run-out compensation of the line-scan results using the point sensor data requires synchronizing both sensors in a way that they measure height values with an identical sampling interval and constant phase shift. Since both sensors require an optical path length modulation, a single signal generation device is used to generate a shared stimulation signal for both sensors. The signal is amplified by two different amplifiers respecting the varying amplitude requirements and avoiding mutual electrical influences of both actors. The signal generation device contains a digital signal processor that is also used for sampling and evaluating the intensity values of the point sensor and triggering of camera images of the line sensor at equidistant steps synchronous to the excitation signal.

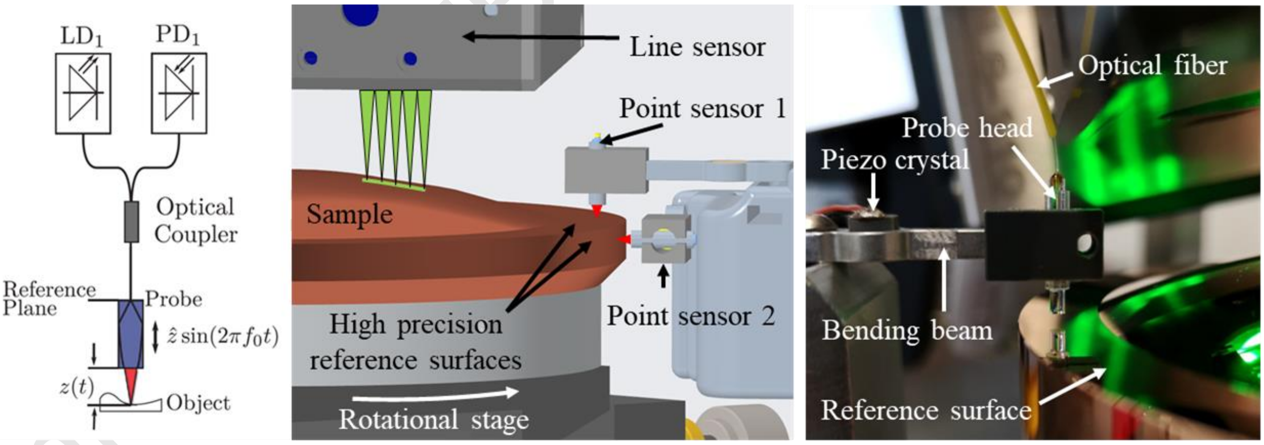

Figure 3: left: schematic setup of the interferometric point sensor [6]; center: scheme of the sensor arrangement with line-sensor, two point-sensors and the corresponding reference surfaces; right: fiber-coupled point sensor element with piezo actuated bending beam and diamond turned high precision reference surface.

REALTIME EVALUATION

The evaluation of the measurement data is carried out in real-time for both sensors using similar computation time reducing single-frequency DFT algorithms. These algorithms require an initialization measurement to detect the dominant frequency of the interference signal. Since this frequency is influenced by the amplitude of the actuator modulating the optical path length, the initialization is repeated if certain sensor parameters are changed. After the frequency is determined, up to two phase values at this frequency are calculated during each actuator period. These phase values are unwrapped, converted to height values using the spectral centroid of the illuminating laser diode or LED and stored. The actuator is driven at a frequency of 1 kHz while recording two height values per period. Thus, the mean duration for the evaluation process of one height value must be less than 500 µs.

The point sensor uses a STM32 ARM microcontroller to sample and evaluate the amplified voltage signal of the detector signals. The line sensor's data is evaluated by a multi-threaded evaluation module that is capable of either using several threads of a central processing unit (CPU) or the unified CUDA-cores of a NVidia graphics processor (GPU). To verify the real-time capability of the module, several line-sensor measurements are evaluated varying the number of processor threads and activated camera pixels while the average time for the evaluation is measured. Figure 4 displays the measured mean computational time to evaluate one height value for each captured camera pixel depending on the amount of evaluating threads of an Intel Core i7 6700K CPU. The measurement shows that even the worst case for this setup of evaluating 4060 camera pixels using a single evaluating thread is capable of evaluating the measurement data in less than 500 µs abided by the introduced real time constraints. For comparison, the computational time using a Nvidia GTX1080 GPU is shown. The results clearly indicate that using a GPU for this kind of application does not bring any time advantage compared to the evaluation using a CPU, although the processing power of the GPU is a multiple of that of the CPU (GTX1080: ~8,000 GFLOPS, 6700K: ~100 GFLOPS). This might be caused by the comparatively small amount of data that has to be transferred to the graphics card's video memory at a time (~190 kByte per height value) or by a not fully optimized evaluation procedure.

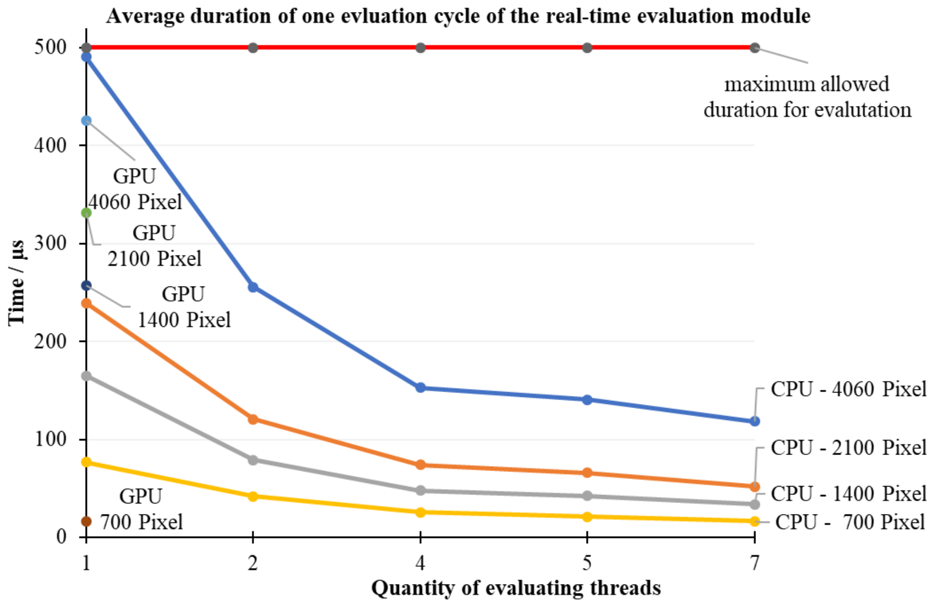

Figure 4: Comparison of the average duration of an evaluation cycle for the activated camera pixels using the real-time evaluation software module based on either GPU (NVidia GTX1080) or CPU (Intel Core i7 6700K).

RUN-OUT COMPENSATION

The following procedure assumes that any run-out of the rotational object stage will affect the measured height data of both, the line sensor and the point sensor, in a similar way. Thus, the deviation of a known reference surface and the measured height data measured by the point sensor can be used to compensate for the run-out of the line sensor's height data. If the geometry of the reference topography is perfect or at least the spatial frequency range of the reference topography is known, this method can be used to compensate any disturbances aside this range giving an advantage compared to frequency-based filter methods. To verify this assumption the topography of the high precision reference surface is determined. This is achieved by several subsequent point-sensor measurements of the same track on the specimen's reference surface. For each measurement, the profile of the topography is calculated (Figure 5, a) considering the maximum spatial frequency of the reference topography. This profile is used to compensate for the unknown height offset and the phase shift between the different measurements. The height offset is a result of the point sensor's evaluation algorithm that is only capable of measuring relative height changes during a scan. The first height value that is measured for each scan is set as reference for each subsequent value. The phase shift of the data is an effect of a slightly varying acceleration trajectory and an inaccurate starting position of the rotational axis. First, the height offset is compensated by subtracting a linear fit of the profile data from both the profile itself and the measured height values (Figure 5, b). Afterwards, the compensation of the phase shift is performed using a cross-correlation algorithm and shifting the measurement data to the maximum correlating phase-position (Figure 5, c). The accuracy of this shifting is increased by linear interpolation of the measurement data sets, allowing the shift of the data with sub sampling interval accuracy. The mean of the shifted profiles is calculated and stored as calibrated reference topography. During each following measurement, the difference of the height values measured by the point sensor and the calibration profile is scaled and subtracted from the line-sensor's height data, again using a cross correlation function in order to compensate for mean profile phase shifts of each measurement. The scaling factor corresponds to the ratio of the radial distance of both surface scan positions to the center of rotation and is optimized during evaluation. Figure 5 shows the calibration and the evaluation process using exemplary measurement data.

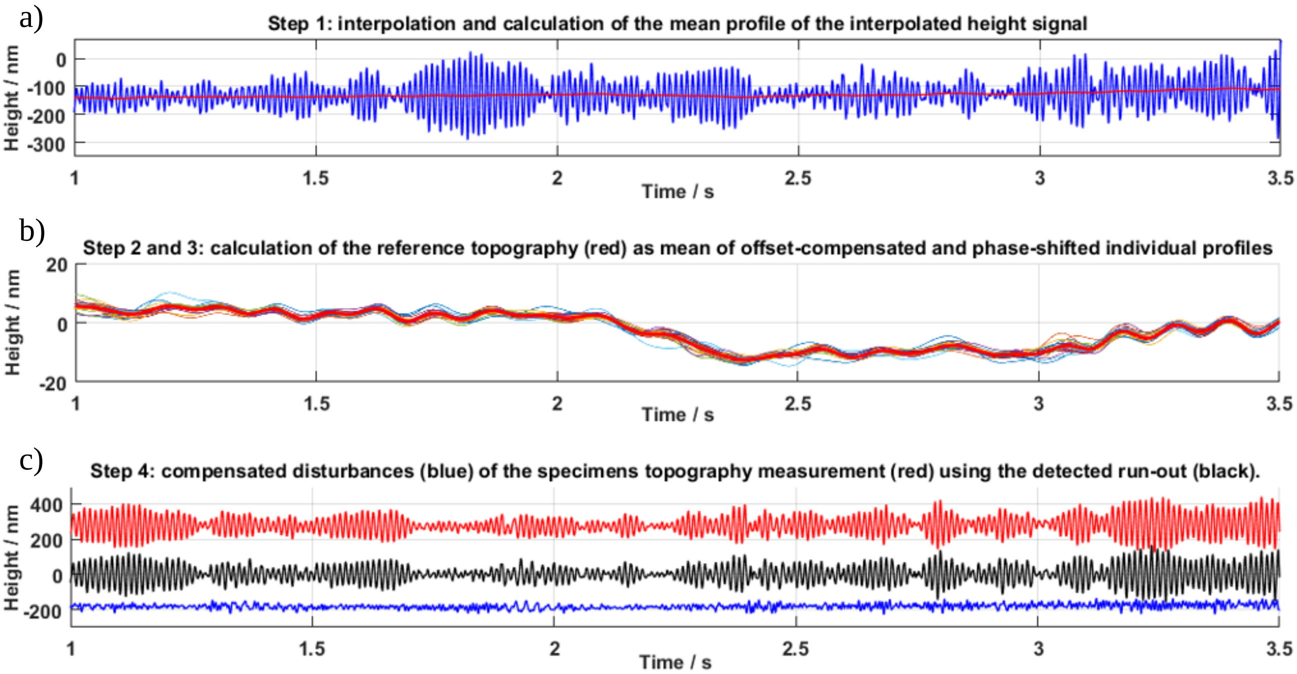

Figure 5: Calibration and measurement process of the run-out compensation for the line sensor measurement; a) section of a single point sensor measurement (blue) and the corresponding calculated surface profile (red); b) phase-shift and offset compensated surface profiles of several reference measurements and the calculated mean (red) used as calibrated reference profile for run-out-detection; c) Result of a run-out compensation (blue) of a line-sensor measurement (red) using the scaled measured run-out of the rotational axis (black).

To quantify the compensation of the run-out, each presented measurement process is repeated 30 times. The mean profile of the measured sample surface is determined likewise the corresponding profile of the reference surface is determined as discussed before. It is used to calculate the standard deviation of the "roughness" of each measured dataset of the line sensor without and with the run-out compensation.

MEASUREMENT RESULTS

Figure 6 shows the result of the measured height values of a single pixel of the high precision machined specimen that is rotated by 5° during the measurement. The red line shows the uncompensated results from the line-sensor, the black line represents the detected run-out of the rotational axis. The blue line represents the run-out compensated height profile. The standard deviation of its roughness is decreased by ~74% from ~37 nm to ~9 nm, the peak-to-peak value are compensated by 70 % from ~250 nm to ~74 nm.

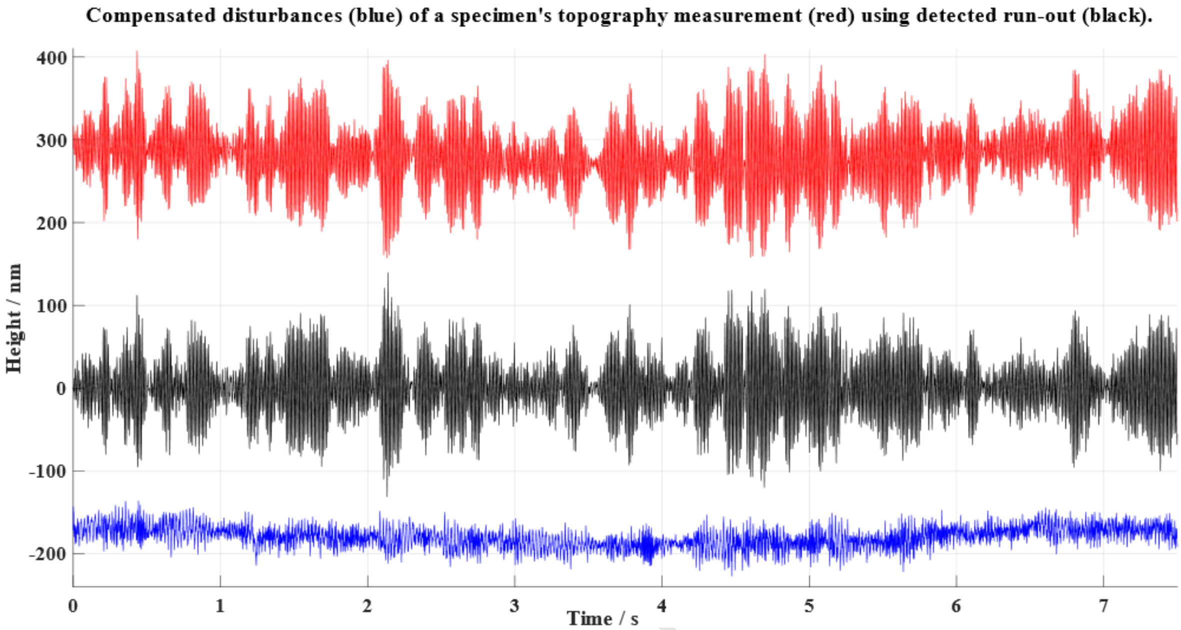

Figure 6: Measured profiles of a specimen’s surface (red), detected run-out of the rotational axis (black) and compensated measured height profile (blue).

To demonstrate the performance of the compensation procedure for the evaluation of 2-dimensional measurement data, Figure 7 shows a measurement result of a line-sensor scan without and with the run-out compensation. The mean “roughness” of the measured 3D topography data is compensated by ~75% from ~46 nm to ~11 nm.

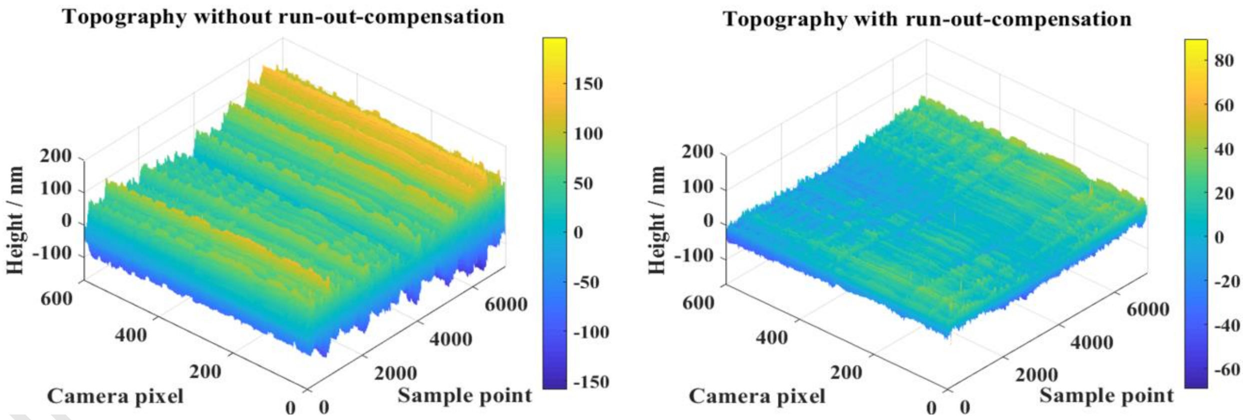

Figure 7: Result of a line-sensor topography scan without (left) and with compensation (right) of the run-out of the rotational object stage.

CONCLUCSION AND OUTLOOK

The presented measurement results show, that an up-to-date processor is capable of evaluating measurement data of the presented line-sensor in real-time using a multi-threaded evaluation software. Evaluation by using a graphics-processing unit does not bring any time advantage compared to the evaluation using a CPU.

Line-sensor measurement results indicates, that the standard deviation of the measured "roughness" is mainly influenced by the run-out of the rotational object stage. These measurement artifacts can be reduced by more than 70% using simultaneously measured results of an interferometric point sensor that is measures a well-known high-precision machined reference surface. Remaining measurement artifacts might be caused by errors in movement of the rotational object stage that are only directed along the rotational axis of the object stage. Compared to run-out errors of the axis of rotation, these movements evenly affect every radial position of the sample and thus do not have to be scaled corresponding to distance to the center of rotation. Using the current setup, it is not possible to separate those artifacts from the run-out errors. A second point-sensor measuring at the opposite circular position of the reference surface could be used splitting these different movement errors, further improving the quality of the line-scan. Further, a point sensor with a higher sample rate could be used to achieve smaller sampling intervals, thus increasing the maximum detectable frequency of disturbances.

The current compensation process is done subsequent to the measurement and takes from a few seconds to few minutes depending on the used parameters and the size of the data-set. Given that the height data of both sensors are evaluated in real-time and are available while the measurement is performed, the process could be integrated to the real-time evaluation module as well, eliminating any expenditure of time for the compensation.

Finally, it should be mentioned that the results presented in this contribution are obtained from preliminary investigations in order to demonstrate the proof-of-principle of the compensation method. Future work based on 360° measurements and more sophisticated compensation and data analysis strategies are necessary to evaluate the full potential of the method.

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