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Integration of a step gauge measurement capability at the PTB Nanometer Comparator – concept and preliminary tests

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Abstract

To meet the increasing uncertainty demands for the calibration of tactile coordinate measuring machines the PTB aims to provide calibrated artefacts with an uncertainty in the range of 30 nm. Therefore, the Nanometer Comparator will be upgraded with a tactile sensor system to add the capability to measure step gauges. A concept of the integration of a tactile sensor into the machine setup is presented and two different sensors were analysed by repetitively contacting a gauge block face. With a sensor based on a silicon flexure and two fibre interferometers a (1σ) repeatability of less than 7 nm was achieved.

1 Introduction

The Nanometer Comparator (NMC) is the national standard of Germany for the calibration of length graduations. It is used for the calibration of line scales [1], photo masks [2] and encoder systems [3] to disseminate the unit of length to industry. It features a slide with a moving range of up to 600 mm whose position is controlled using the feedback of three interferometers working in vacuum, among other measurement systems. A Lorentz actuator was integrated into the drive system to compensate small position variations based on the feedback of the vacuum displacement interferometer (X-interferometer). This recent update resulted in a variation of the slide position with a standard deviation of 0.3 nm at any position of the moving range [4] and a linearity of the motion in the range of ±1 nm [5]. The NMC is also equipped with three Y-interferometers enabling straightness measurements [6] and potentially providing a control of the horizontal straightness motion error within the sub-nanometre range [7]. To minimize measurement distortions caused by variations of the ambient conditions, the NMC is located inside a climatized cabin with a minimal amount of heat source, which lead to temperature variations of the moving slide of less than 1 mK during the calibrations. Additionally, the machine is supported by an active vibrations isolation system. Avoiding the limitations of correcting the refractive index, the beam paths of the X-, yaw and pitch interferometers are inside a vacuum chamber, which results into a standard uncertainty of the X-interferometer of less than 0,2 nm over a measurement distance of 300 mm. Currently, it is planned to integrate another two interferometers as feedback of a roll angle control. In summary, the NMC provides a moving slide whose position is potentially controlled in all six-degrees of freedom within the single-digit nanometre range. Because the roll angle deviations are minor importance for many one-dimensional measurements the NMC is already now a good choice to implement new measurement tasks aiming nanometre uncertainties, like step gauge calibrations.

Since the Nanometer Comparator is used for a numerous of different calibration tasks, it must be adapted for the calibration of step gauges. The moving slide, where the measurement object is placed at, has moving range of 600 mm in X-direction, but is limited to ±5 µm in Y- and Z-direction. Therefore, the tactile sensor measuring the faces of step gauges must be moved in Z-direction with an additional stage. For security reasons, the moving range of this additional stage should be 50 mm with the requirement of a reproducibility of the position of ±1 µm in Y- and Z-direction. The expected guiding errors of the additional Z-stage would limit the measurement uncertainty in case a conventional commercial tactile sensor is used, which is shown in the section 3.2. Therefore, two different, home-made tactile sensors were tested. One of them used a fibre interferometer to measure the deflection of the tactile sensor. In preparation, this fibre interferometer had been qualified with the NMC, as described in section 3.1. Preceding, in section 2, the concept of the integration of the step gauge calibration capability is described. Part of the calibration of step gauges is the assessment of the parallelism and flatness of individual faces. This will be realized in separate measurements using an auxiliary bridge of the Nanometer Comparator, which will also be used for the alignment of the step gauges, as described in section 2.2. For the determination of the sphere diameter of the tactile sensor, it is planned to use calibrated gauge blocks. This will additionally result in a first comparison of the NMC with PTB's precision interferometer for gauge block calibrations [8]. But the very first step is the capability to probe a gauge block with a repeatability in the nanometre range.

2 Concept of the integration of the step gauge measurements

2.1 Integration of a tactile sensor at the Nanometer Comparator

The step gauge will be placed inside the sample carriage made of Zerodur [10] on the moving slide, as illustrated in figure 1. The moving mirrors of all interferometers are also attached to the sample carriage. In this way, the interferometer mirrors are linked with the measurement object in a stiff way and temperature variations cause only minimal distortions. The slide is moved in X-direction, while its X-position is controlled by linear motors and a Lorentz actuator based on the feedback of an encoder systems and the vacuum X-interferometer [4]. The slide is supported by four air bearings resulting into a nearly frictionless movement and another four air bearings are used to guide the slide inside a grove of the granite base. All air bearings are connected via piezoelectric actuators to the slide to realize yaw, pitch, Z- and Y-movements. These piezoelectric actuators limit the potential moving range of the slide to ±5 µm in Y- and Z-direction. Therefore, an additional Z-stage must be integrated moving the tactile sensor for the calibration of step gauges. The slide is moving relatively to the bridge with all the reference mirrors of the interferometers attached to it. The Z-stage as well as the tactile sensor fixed to it will also be mounted to this bridge.

Since the NMC was not specially designed for step gauge calibrations, it has the space restrictions for potential measurement objects, which are illustrated in figure 2. The tactile sensor must be moved up to 50 mm in Z-direction. According to Abbe's criteria, the faces of the step gauge should be probed

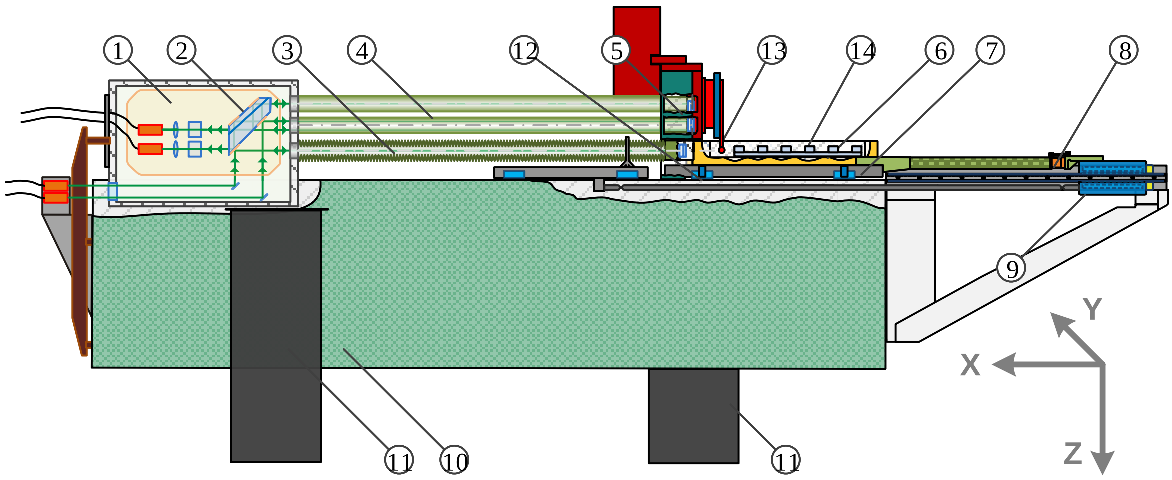


Figure 1: Schematic drawing of the Nanometer Comparator: 1: vacuum chamber for the X-, yaw- and pitch-interferometers, 2: X-interferometer beam splitter [9], 3: vacuum bellow connecting the moving slide and the vacuum chamber guiding the measurement beams, 4: pipes for the reference beams of the interferometers, 5: bridge with all reference mirrors, 6: sample carriage with long-range Y-mirror and moving mirrors of the vacuum interferometers [10], 7: moving slide, 8+9: Lorentz actuator and linear motor for the positioning of the slide, 10: granite base (size: 3,15x0,8x0,7 m³), 11: active vibration isolation, 12: piezo elements connecting the air bearings and the slide 13: tactile sensor with Z-stage connected to the bridge, 14: step gauge mounted on the sample carriage.

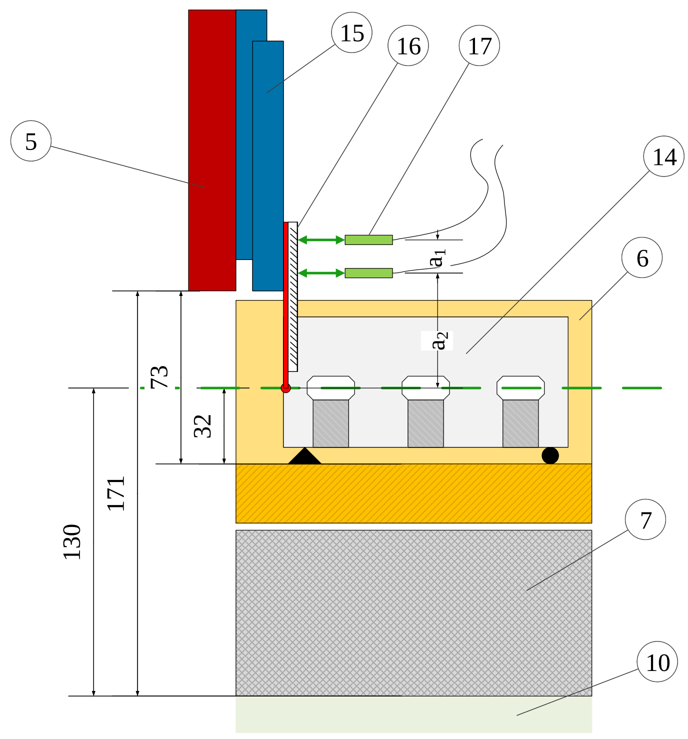


Figure 2: Detailed view of the space restrictions for measurement objects and the arrangement of the tactile sensor at the Nanometer Comparator: 5: bridge, 6: sample carriage, 7: Moving slide, 10: granite base, 15: Z-stage with moving range of 50 mm, 16: tactile sensor, 17: fibre-fed interferometer head.

collinear with the measurement line of the X-interferometer to avoid errors resulting from angle variations. This line is 41 mm below the bottom side of the bridge located above the slide. During the load and alignment process of the step gauge, the tactile sensor should be parked above the bottom side of the bridge to prevent physical damage. The height of a measurement object must be below 70 mm, its width below 65 mm in case it is longer than 470 mm and its length below 550 mm if all faces should be measured within one orientation.

The integration of the Z-stage leads to an unstable connection between the interferometer reference mirrors mounted on the bridge and the tactile sensors. Therefore, the positioning and guiding errors as well as position stability of the Z-stage can cause additional uncertainty contributions for the step gauge calibration due to the flatness and parallelism deviations of the individual faces of the step gauge. Assuming a variation of the relative angles of the face of 100 µrad a reproducibility of the Y- and Z-position of ±1 µm is needed for the probing sphere to guarantee a negligible error. Therefore, the Z-stage has a position sensor and appropriate specifications of the horizontal straightness motion errors as well as motions related to angular deviations. A reproducibility of its vertical motion error (X-direction in case the stage is assembled at the NMC) in the single-digit nanometre range cannot be realized without disproportional effort. Therefore, it must be measured. To realize this measurement with a reproducibility in the single-digit nanometre range, a mirror and interferometers fixed directly to the bridge are integrated in addition to the tactile sensor. Since, the interferometer is measuring at least 45 mm (distance a_2 in figure 2) above the probing point of the sphere a second interferometer must be integrated to compensate for pitch angle variations of the Z-stage [11].

2.2 Alignment concept of the step gauge

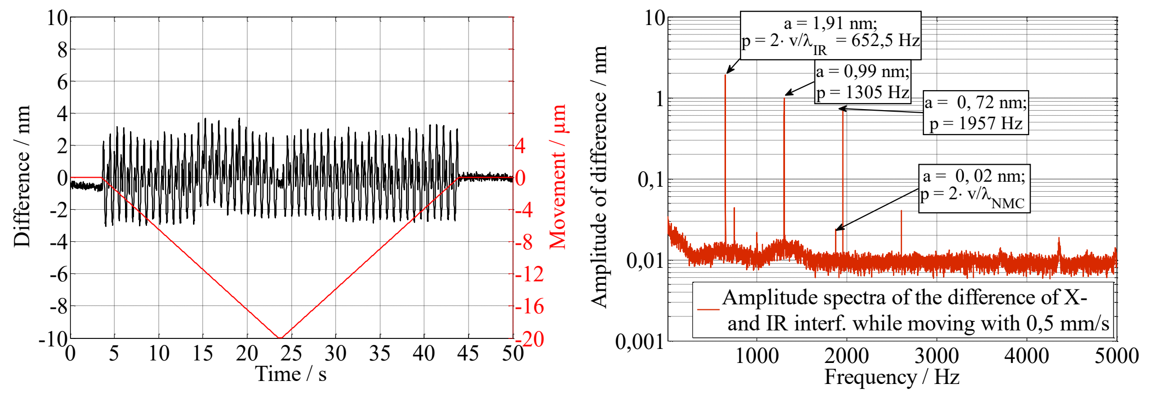
The use of a highly sensitive but only one-dimensional tactile sensor requires a complex alignment procedure of the step gauge. An additional 3D tactile probe mounted at an auxiliary bridge of the Nanometer Comparator will be used for this alignment. The auxiliary bridge can be moved manually in X-direction and in Y-direction using a linear motor. Its position is measured using an encoder system with a reproducibility of 1 µm. The relative position of the two tactile sensors must be determined in a first step, since it will not be possible to probe the tactile sensor mounted at the bridge directly with the 3D sensor. Therefore, a sphere or a roof mirror on a manual Y-stage inside the sample carriage has to be probed with both sensors to link the coordinate systems of the two bridges. Depending on the design of the step gauge the side walls or reference marks will be used for its alignment. Using the design parameters of the step gauge the desired measurement trace must be adjusted collinear with the X-Interferometer as well as its yaw and pitch angle parallel to the general moving direction of the slide to minimize cosine errors. Because the yaw and pitch feedback control loops reduce the angle variations of the moving slide to below 1 µrad a detailed alignment of the tactile sensor should not be necessary. In general, the fabrication tolerances of the holders should be adequate to reach the targeted uncertainty of 30 nm. For more precise adjustment of the tactile sensor position the yaw and pitch angle of the slide can be varied while the tactile sensor is contacting a face [12]. The variation of its signal will remain zero in case the tactile sensor is placed collinear with the measurement direction of the X-interferometer and a negligible angle of the faces. Assuming specifications of common step gauges, the parallelism of the faces can limit the determination accuracy of the Abbe offset to 0.1 mm. The alignment of the step gauge Z-position can be realized measuring the heights of the faces while moving the tactile sensor in Z-direction and detecting their edges. For objects of known geometrical size, the alignment of the Z-position can be based on an auxiliary gauge bock and a confocal sensor, to align the step gauge to specific height relatively to the slide.

3 Concepts of tactile probes

An interferometer fixed to the bridge of the Nanometer Comparator will be used to measure the repeatability of the vertical straightness motion errors of the Z-stage. The errors and the stability of this fibre interferometer influence the measurement results directly. Therefore, these errors were analysed in preliminary experiments using the vacuum interferometer of the Nanometer Comparator. In a second step, two different concepts of tactile probes were tested by repetitively measuring the position of a gauge block face leaving out the Z-movement in the first place.

3.1 Characterisation of the interferometer for the tactile sensor

The interferometer system under test is a commercially available system. It consists of up to three miniaturised Michelson type measurement heads and a main unit including a stabilized laser source, signal processing and data interfaces. It is using a laser diode with a wavelength of 1532 nm and is therefore referred as IR interferometer in the further description. The homodyne system is fully fibre coupled with the advantage, that heat sources such as the light source and the detection unit are separated from the tactile sensor. With a diameter of 4 mm and a length of 13 mm the interferometer heads are smaller than many commercially available interferometer heads. The frequency of 1532 nm distributed-feedback laser diode is modulated to generate quadrature signals [13]. This leads to the drawbacks of a dead path of at least 13 mm required for the interferometers so that the variations of the ambient



(1) PNL in time- domain *(2) PNL in frequency-domain*

Figure 3: Periodic nonlinearities (PNL) of the IR interferometer evaluated in two comparison measurements with the vacuum X-interferometer of the NMC (Note: two data sets with different speeds of the slide are shown).

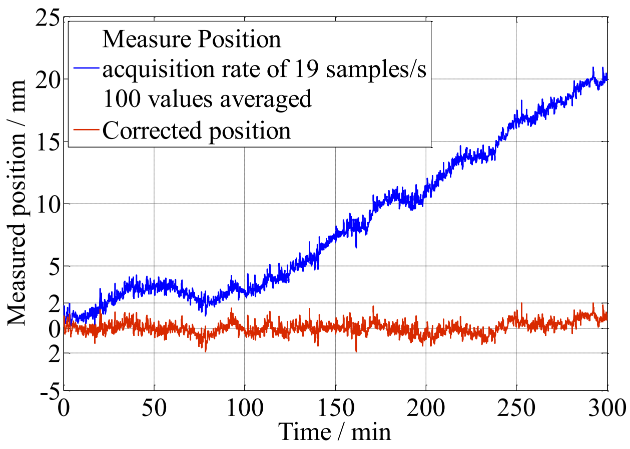


Figure 4: Stability of the IR interferometer over 5 hours with a compensation of the 24 mm long dead path, which is provided by the system.

conditions influence their long-time stability and periodic nonlinearities [14]. The long-time stability and the periodic nonlinearities of the system have the mayor impact on the uncertainty during the planned step gauge measurements. Therefore, these parameters were evaluated in preliminary experiments using the vacuum X-interferometer.

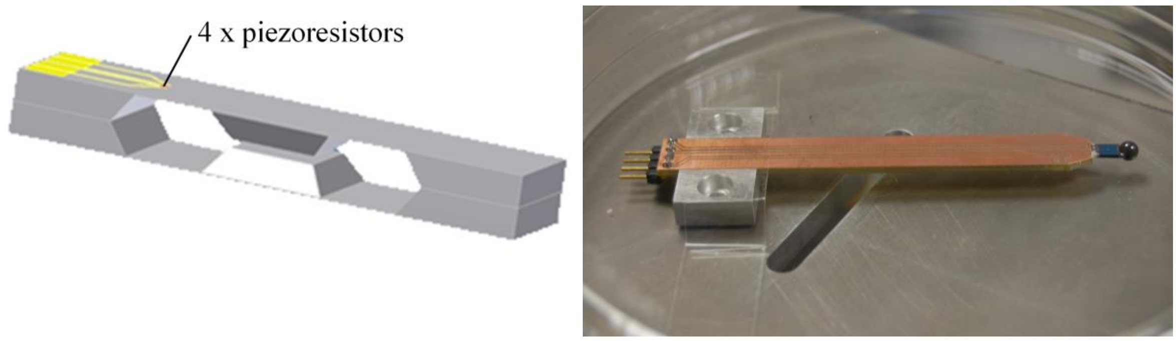
For this purpose, the miniaturised interferometer head was fixed at a kinematic mirror mount, which was attached to the bridge of the NMC. The signal of a quadrant diode fixed on the moving slide was used to align the measurement direction of the IR interferometer head parallel to the general moving direction of the slide. Afterwards, a mirror fixed also at a kinematic mirror mount was placed inside the sample carriage and adjusted until the maximum interference contrast was reached using the signal amplitude provided by the interferometer electronics as indicator.

The periodic nonlinearities of the IR interferometer system were determined by moving the slide with a constant speed over a certain distance. The change of the slide position was measured synchronously with the vacuum X- and the IR interferometer by externally triggering both data acquisitions. Figure 3 exemplifies the evaluated periodic nonlinearities of the IR interferometer in the time- and frequency-domain [15]. The amplitude spectra of the difference of the two interferometer systems illustrates the presence of relevant periodic nonlinearities of the first, second and third-order. Due to their origin given by the generation of the quadrature signals, these three signal deviations are phase-locked and result into a conservative estimated uncertainty contribution (sinusoidal error leads to U-shape distribution) of:

$$u_{\mathrm{PNL}} = \sqrt{\frac{1}{2}(a_1 + a_2 + a_3)^2} = 2.6\ \mathrm{nm}. \qquad (1)$$

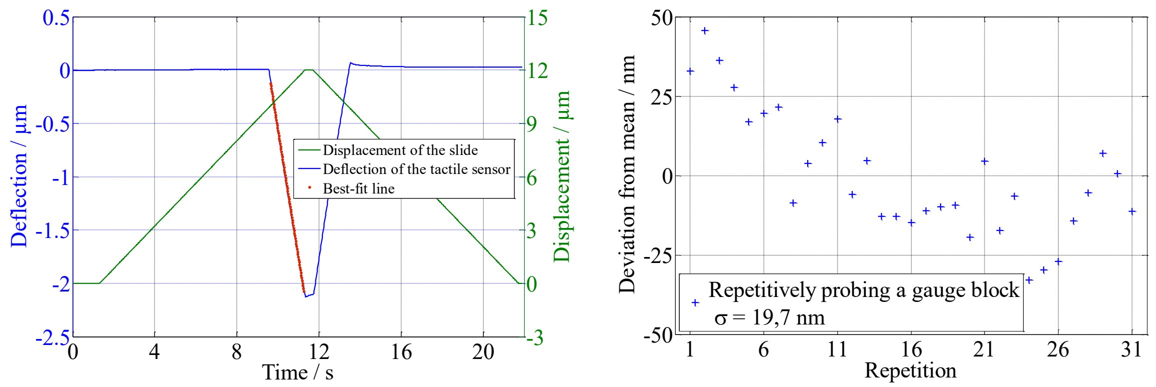
Since, their more or less mathematical origin the periodic nonlinearities of the IR interferometer depend on the signal quality. Therefore, they can increase up to a factor of two in case the interferometer head is used close to its minimal working range of 13 mm. But increasing the dead path of the IR interferometer to more than 15 mm will also increase the influence of the refractive index variations. These deviations are uncorrelated for two interferometers arranged with an interspace larger than 11 mm under the environmental conditions of the NMC [16, 17]. An advantage of the used wavelength is the smaller sensitivity to turbulences of the air compared to visible light. Therefore, the standard deviation of the measured position caused by refractive index fluctuations was below 1 nm even for larger dead paths up to 100 mm under laboratory conditions.

The dead path is provided with a reproducibility of 0.1 mm by the system. Therefore, long-term variations of the refractive index can be compensated. The time required for the measurement of one step gauge will depend on its size and will in most cases exceed 30 minutes. The drift of the IR interferometer system during this period causes directly a measurement error, since it will define the zero position of the tactile probe. A long-term test shown in figure 4 revealed that the system remains stable in the range of ±2 nm over 5 hours.



(1) Schematic view of the flexure hinge *(2) Picture of the tactile sensor*

Figure 5: Tactile sensor 1 based on a silicon flexure with piezoresistors.



(1) Deflection of the tactile sensor *(2) Repeatability of probing a gauge block*

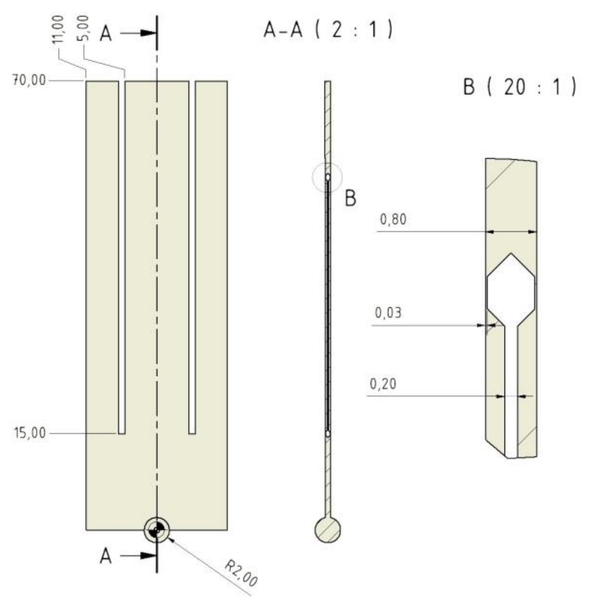
Figure 6: Results of probing a gauge block with the tactile sensor 1 – deflection and repeatability.

In summary, it is feasible to measure the position of the tactile sensor with a reproducibility in the single-digit nanometre range using the IR interferometer over the whole measurement time. But, additional measurement deviations can occur due to the drift of the mechanical holders with temperature variations and vibrations introduced by the Z-stage.

3.2 Tactile sensor 1 (electrical)

Figure 5 shows the first sensor type investigated. This tactile sensor was converting its deflection using four piezoresistors in a Wheatstone bridge arrangement [18] to a voltage. The basic structure of the sensor consists of two bonded silicon chips with overall dimensions of 6.5 mm x 3.5 mm x 0.8 mm. At some positions, the thickness of the material is reduced to 20 µm building the flexural hinges of the double beam structure, as illustrated in figure 5. For the machining of the silicon anisotropic wet-etching processes where used. To enable the free movement of the structure the thickness of the two centre bosses must be reduced in an additional etch step. To realize the sandwich structure two wafers of structured silicon are needed which are connected by silicon direct bonding. A standard dicing saw was used afterwards to separate the sensor dies leaving the compliant structure of the sensor. Piezoresistive sensors arranged as a Wheatstone bridge were fabricated on the backside of the membrane by a focused ion-beam doping technique and act as sensor elements. By applying a force to the sensor structure mechanical stress occurs at the position of the flexural hinges. This mechanical stress was converted in an electrical output signal, amplified by an amplifier module and directly acquired by the phase meter boards of the interferometers [5]. Therefore, the acquisition of the interferometer and probe data occurs highly synchronous.

The upper side of the silicon flexure was glued to a circuit board (PCB), while a sphere made of Si3N4 with a diameter of 4 mm was attached to the other site. The PCB was glued on an aluminium holder to



(1) Drawing of the "stylus" of the tactile sensor 2

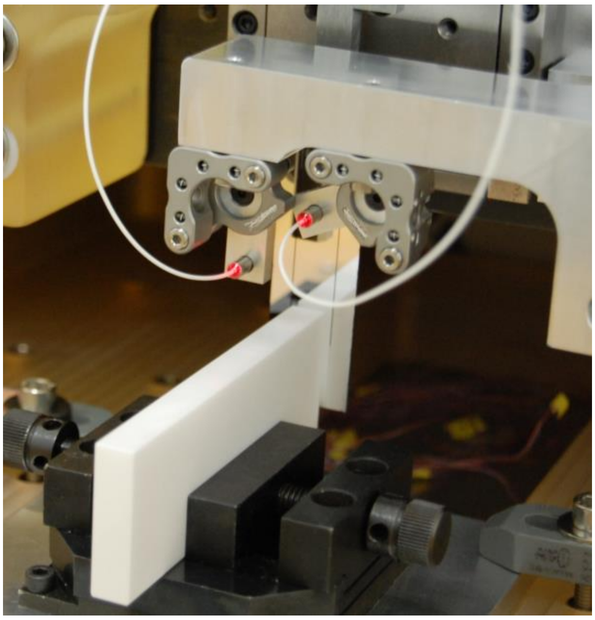
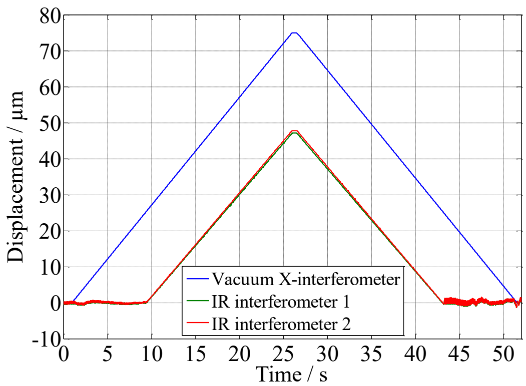
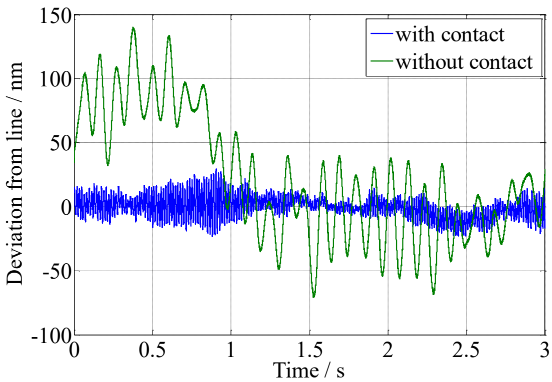

(2) Picture of the tactile sensor

Figure 7: Tactile sensor 2 based on a silicon flexure with aluminium coating.



(1) Deflection of the tactile sensor



(2) Vibration of the stylus

Figure 8: Optical measurement of the stylus deflection.

fix the tactile sensor on the Z-stage, as illustrated in figure 5. In case the sphere is touching a surface, the silicon membranes are deflected and the voltage is changed.

In a first step, a gauge block was fixed on the moving slide of the NMC (see picture in figure 7 for details) and one face was probed repetitively. Therefore, the slide was moved with 1 µm/s over 12 µm forwards and backwards. The voltage signal from the tactile sensor as well as the position values of the slide had been measured with an acquisition rate of 48,8 kHz. After the measurement, each 1000 values were averaged. The contact point was calculated as the zero-force point by fitting a straight line to the voltage curve, as shown in figure 6. The zero-voltage level of the sensor was subtracted for each probing point to minimize the influence of the potential drift of the amplifier offset compensation and the piezoresistors. This reduces the standard deviation for repetitively measuring the position of a gauge block face from 39 nm to 20 nm.

The design principle of the tactile probe and the signal generation were not limiting the repeatability, despite the PCB was also deflected. The copper layer of the circuit board was used as reflector for the IR interferometer and its deflection was measured. Using the interferometer signal to determine the zero-force point resulted into a similar repeatability. Therefore, it was suspected that the instable connection between the reference mirror of the vacuum interferometer and the tactile sensor, which may result in an undetermined angle variation between the two systems compared limits the performance. This will be clarified in detail in the next section.

3.3 Tactile sensor 2 (optical)

The second tactile probe consisted of an etched silicon stylus coated with aluminium. The stylus is illustrated in figure 7 and its deflection was measured with two IR interferometer heads. In opposite to conventional styli a bending of the stylus is a desired effect. Therefore, the thickness of the silicon wafer was reduced at certain positions by wet-chemical etching resulting in a double beam configuration with flexure hinges. This configuration enables a nearly parallel movement of the two mirrors arranged on both sides of the flexure. To avoid a reduction of the signal amplitude of the two interferometers measuring the deflection, the angle variations caused by the deflection of the stylus must be minimal. Additionally, these mirrors had a length of 70 mm to measure the repeatability of the motion errors of the Z-stage without interruption of the interferometer beams. A Si3N4 sphere with a diameter of 4 mm was glued to the lower end of the stylus. The chosen dimensional parameters of the stylus resulted into a potential elastic deflection of several hundred micrometres, but also into a high sensitivity to vibrations. Without contact to the surface the sphere oscillated with an amplitude up to 1 µm with the eigenfrequency of the stylus of 10 Hz. These oscillations were significantly reduced in case the sphere was in contact with the gauge block. Then the amplitude was below 30 nm and the eigenfrequency was shifted to 66 Hz

The two IR interferometer heads measuring the deflection of the stylus were arranged at different Z positions. Their interspace was approximately three times smaller than the distance between the first interferometer head and the sphere in collinear position with the X-interferometer of the Nanometer Comparator. In this arrangement, a gauge block moved with 5 µm/s was contacted 102 times. Each time a line was fitted to the interferometer data with a deflection of the stylus between 6 µm and 46 µm using least-squares method. In opposite to the electrical signals of the tactile sensor 1 the zero-force point was evaluated using only the parameters of the fitted line without subtracting the zero-deflection level for each point. As shown in figure 9, a usage of only one interferometer would result into a similar repeatability as reached with the electrical tactile sensor 1. But, calculating the difference of the two interferometric measurements and compensating for angle variations resulted into a reduction of the standard deviation to 6.4 nm. The remaining deviations are likely to be caused by the periodic nonlinearities of the IR interferometer, the influence of refractive index variations and mainly the oscillation of the stylus.

Due to its minor importance for the presented unidirectional measurement, for both tactile sensors the deformation of the sphere and the gauge block had not been corrected yet. The influence of the comparatively small probing forces in the range of 10 µN will be further analysed. During the presented preliminary experiments, the repeatability was independent of the deflection of the stylus.

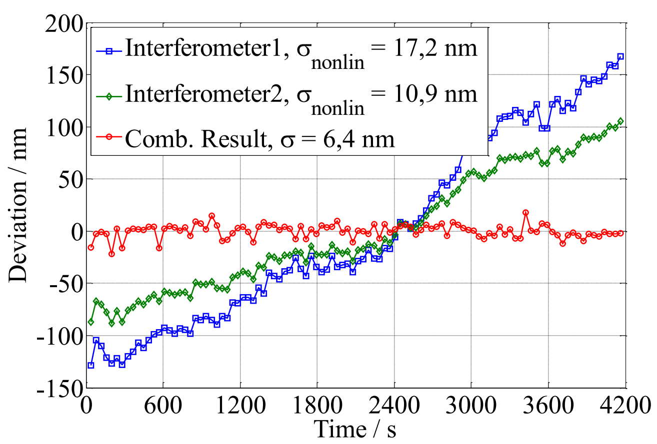


Figure 9: Repeatability of measuring the position of a gauge block face. The deflection of the stylus of up to 48 µm was measured with two interferometer heads arranged at different Z positions to compensate for the angle variations of the tactile sensor.

4 Conclusions and Outlook

The two different tactile sensors had a similar repeatability for measuring the position of a gauge block face. Despite thermalized conditions and probing forces in the range of 10 µN the unstable connection of the stylus with the reference mirror of the vacuum interferometer was the crucial factor limiting the repeatability of both tactile sensors. Since the additional Z-stage is needed to move the tactile sensor, this unstable connection cannot be avoided and, therefore, its influence must be corrected for. A combination of the tactile sensor with two interferometers enabled a compensation of angle variations fulfilling the extended Abbe criteria [11] and resulted in a repeatability of 6.4 nm.

In case the tactile sensor is equipped with two interferometer heads, an additional measurement of a voltage signal is not necessary by using the deflection of the stylus as desired feature. But the required size of the stylus in combination with the comparatively soft flexures to realize a parallel movement of the mirrors with the sphere resulted in an eigenfrequency of 10 Hz and a high sensitivity to vibrations even in the case of contact. Therefore, the oscillations of the stylus limited the repeatability. A reduction of these oscillations will be the focus of future developments. The stylus will be fabricated on basis of thicker silicon wafers also increasing the thickness of the etched membranes. Additionally, a damper based on air suspension will be added. Also, another concept of the tactile sensor will be tested. It will be based on a twin parallel string for parallel movement and a commercial and replaceable stylus for cleaning accessibility and the access to diamond-coated spheres [19]. In addition, a backside coated mirror to transfer parts of the required dead path of the IR interferometers into glass minimizing the influence of variations of the ambient conditions.

The influence of additional heat sources and vibrations introduced by the Z-stage are expected to lead to other significant contributions to the measurement uncertainty. Therefore, further investigations are necessary to find the most suitable stage and a balanced measurement strategy.

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