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A COMPACT TACTILE SURFACE PROFILER FOR MULTI-SENSOR APPLICATIONS IN NANO MEASURING MACHINES

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ABSTRACT

A tactile surface profiler was developed for applications in the nano measuring machine NMM-1. To enable its utilization as part of a multi-sensor concept in an automated sensor changer, a compact design was necessary. The profiler uses a flexure guide made from two circular steel membranes as suspension for the stylus and a focus sensor system to measure its deflection. The profiler was integrated into a NMM-1 to prove its function and investigate its metrological properties. Measurements of different samples showed a reproducibility of few nanometers.

1. INTRODUCTION

At the Institute of Process Measurement and Sensor Technology three nano mesasuring machines NMM-1 (SIOS Messtechnik GmbH) are frequently used for routine measurements and research [1] [2]. Different sensor systems like AFM, 3D-microprobes, white light interferometer and focus sensors are used for the various tasks. To extend the measurement capabilities of the NMM-1 a new tactile surface profiler for roughness and form measurements was developed. The new sensor will also be employed in the multi-sensor concept for the NMM-1 as proposed in [3]. Therefore a compact geometry with a mechanical interface to the motorized sensor changer was necessary. Figure 1 shows an experimental setup.

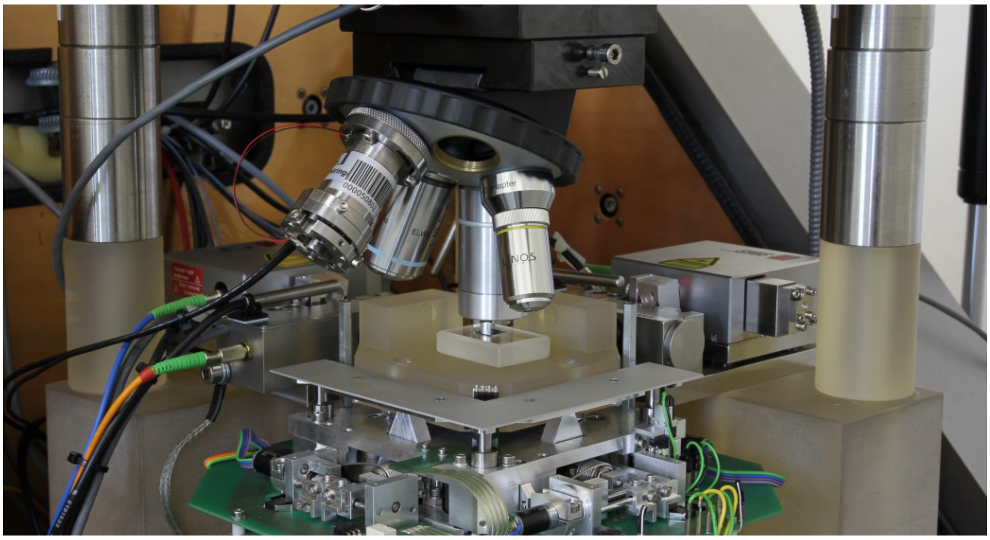

Figure 1: NMM-1, equipped with different sensors: AFM, 50x objective, stylus profiler, Mirau objective (from left to right)

2. MEASUREMENT PRINCIPLE

A standard stylus tip with a tip radius of 2 µm is brought in contact with the sample surface. The stylus tip is connected to a flexure system that guides it along a single degree of freedom and applies the contact force to the sample surface. The position of the tip is measured with sub-nanometer resolution by a laser focus sensor. The scan motion for the profile measurements is carried out by the nano measuring machine (NMM).

3. SENSOR DESIGN

The design of the sensor system had to take several restrictions and requirements into account that are unique for the proposed application. The automated sensor changer, a motorized 6-position objective revolver, limits the diameter of the cylindrical sensor to 30 mm. The distance from the mounting point to the tip, where the contact with the sample occurs, needs to be matched with the other sensor systems.

At the same time, the profiler should comply with the *"Nominal characteristics of contact (stylus) instruments"* according to [4]. The standard defines a nominal static measurement force of 0.75 mN and a nominal change of the static measuring force of 0 N/m. The second condition cannot be fulfilled by the presented profiler, as the stiffness of the suspension needs to be larger than 0 N/m. The variation of the measuring force will be minimized by the NMM, as shown in section 5.3.2. The employed stylus tip has a tip radius of 2 µm and a cone angle of 60°.

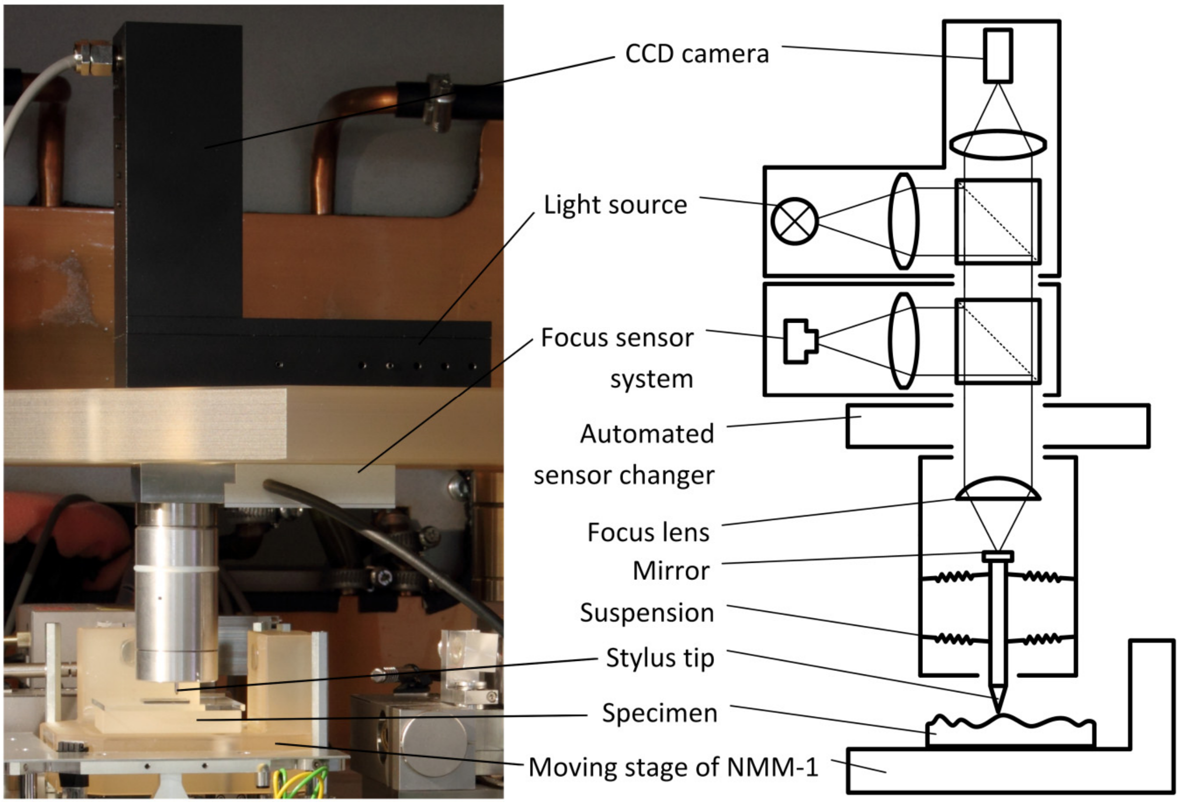

Figure 2: Stylus profiler integrated into the NMM and schematic view

Figure 3: Shape of the steel membranes

The stylus needs a guide system that allows the movement along one degree of freedom (in direction of the tip axis) and locks all other degrees of freedom. Additionally a defined measurement force needs to be applied. Due to the restrictions of the available space a flexure guide, made of two circular, structured metal membranes was chosen. The primary goal for the design was to achieve a high stiffness perpendicular to the axis of the stylus tip while maintaining a low spring constant in the direction along the tip axis. The high stiffness perpendicular to the stylus is needed to avoid an unwanted movement or tilt in direction opposite to the scanning movement. A low spring constant along the tip axis is needed to minimize changes of the measuring force during measurements as it is directly proportional to the magnitude of deflection. The mass of the moving parts has to be as small as possible, to reduce dynamic forces during measurements and to maintain a high natural frequency.

The suspension system consists of two structured, circular steel (1.1248) membranes, arranged parallel to each other. Figure 3 shows the structure of one of the chosen membranes. At the outer circumference they are fixed at the cylindrical housing of the profiler. At the center they are connected to a ceramic (Al_2O_3) stylus at which also the stylus tip is fixed. A small mirror is attached at the top of the ceramic stylus. The focus sensor measures its deflection at this point.

Installed in the profiler, the membranes are pre-loaded to prevent snap-through buckling during measurements. Figure 2 shows the complete system, integrated in the NMM (without the sensor changer and additional sensors). The light source and CCD camera are not used for the profiler. They are needed for the optical sensors of the multi-sensor system.

The design of the suspension was simulated using FEM software (Ansys) to predict the behavior in its finished state. The spring constant of the flexure guide was calculated as 14.4 N/m in direction of the stylus and 4220 N/m perpendicular to the stylus. The weight of all moving parts is 0.19 g. The membrane was manufactured by chemical etching instead of laser cutting to avoid heat induced changes of the mechanical properties.

4. MEASUREMENT SETUP

The measurement setup consists of a nano measuring machine and the profiler sensor head. The NMM is used to position the sample, perform the scan motion for the measurement and to save the sensor data synchronous with the position data of the sample. The NMM is equipped with interferometric measurement systems and features a positioning range of 25 mm x 25 mm x 5 mm with a resolution of 0.1 nm [2], [5]. The stylus profiler is fixed at the metrology frame of the NMM. It features an analog output signal which is sampled and processed by the controller electronics of the NMM. The system rest on pneumatic vibration isolators and is shielded from air flow and acoustic noise by an enclosure.

5. EVALUATION OF THE PROFILER

5.1 Suspension – Stiffness

The suspension has been simulated during the design process. It was expected, that the real behavior would differ somewhat from the simulated due to uncertainties of the simulation parameters, of the material and the geometrical properties of the spring and the assembly. Therefore measurements to determine the actual stiffness of a single membrane as well as the assembled suspension have been carried out. A linear stage with stepper motor (resolution 0.1 µm) was used to move the membrane spring respectively the assembled profiler into contact with a force sensor. From the measured force, the known stiffness of the force sensor and the movement distance of the linear stage, the spring constant of the single membrane as well as the assembled suspension were calculated. The spring constant of a single membrane was measured with 7.2 N/m, which matches the simulated 7.1 N/m very well. The assembled suspension however has a measured stiffness of 24.7 N/m, a significant difference to the expected 14.4 N/m. With the exact reason yet unknown, this is most probable caused by the additional constraints by the assembly and will be investigated further.

5.2 Calibration

Before measurements with the profiler can be carried out, it is necessary to determine the correlation between the focus error signal from the focus sensor and the displacement of the tip of the profiler. This calibration is carried out in the NMM. Using the positioning stage of the NMM, a rigid part with a flat surface is brought in contact with the stylus tip and moved further upwards through the entire measurement range of the profiler. The signal of the focus sensor is sampled synchronous with the position of the stage. This position data, the length values obtained by the laser interferometers, is used as the reference for the calibration. The obtained characteristic line of the profiler is approximated by a third order polynomial fit and saved as configuration data for the NMM. It is now used to calculate the stylus deflection from the analog sensor signal of the profiler.

5.3 Measurements

For the measurements the stylus tip is brought in contact with the surface of the sample and is further deflected until the setpoint, the measuring force of 0.75 mN, is reached. The sample is then moved in a linear motion to measure a profile line. By using the sensor signal of the profiler, the z-axis of the NMM follows the height profile of the sample surface in order to

hold the defined setpoint during the scan motion. The profile data is combined from the measured stylus deflection and the displacement data of the positioning stage of the NMM.
Three samples with different surface structures have been used to test the profiler: A chirp calibration standard with a sinusoidal structure, a peak to peak amplitude of 1 µm and a varying wavelength [6], and two sample structures with peak to peak amplitudes of 3.4 µm and 90 µm. Figure 4 shows measured surface profiles for all three structures. The distance between the data points along the profile is 30 nm. No filters were applied to the measurement data aside from a linear fit to remove the tilt of the profile.

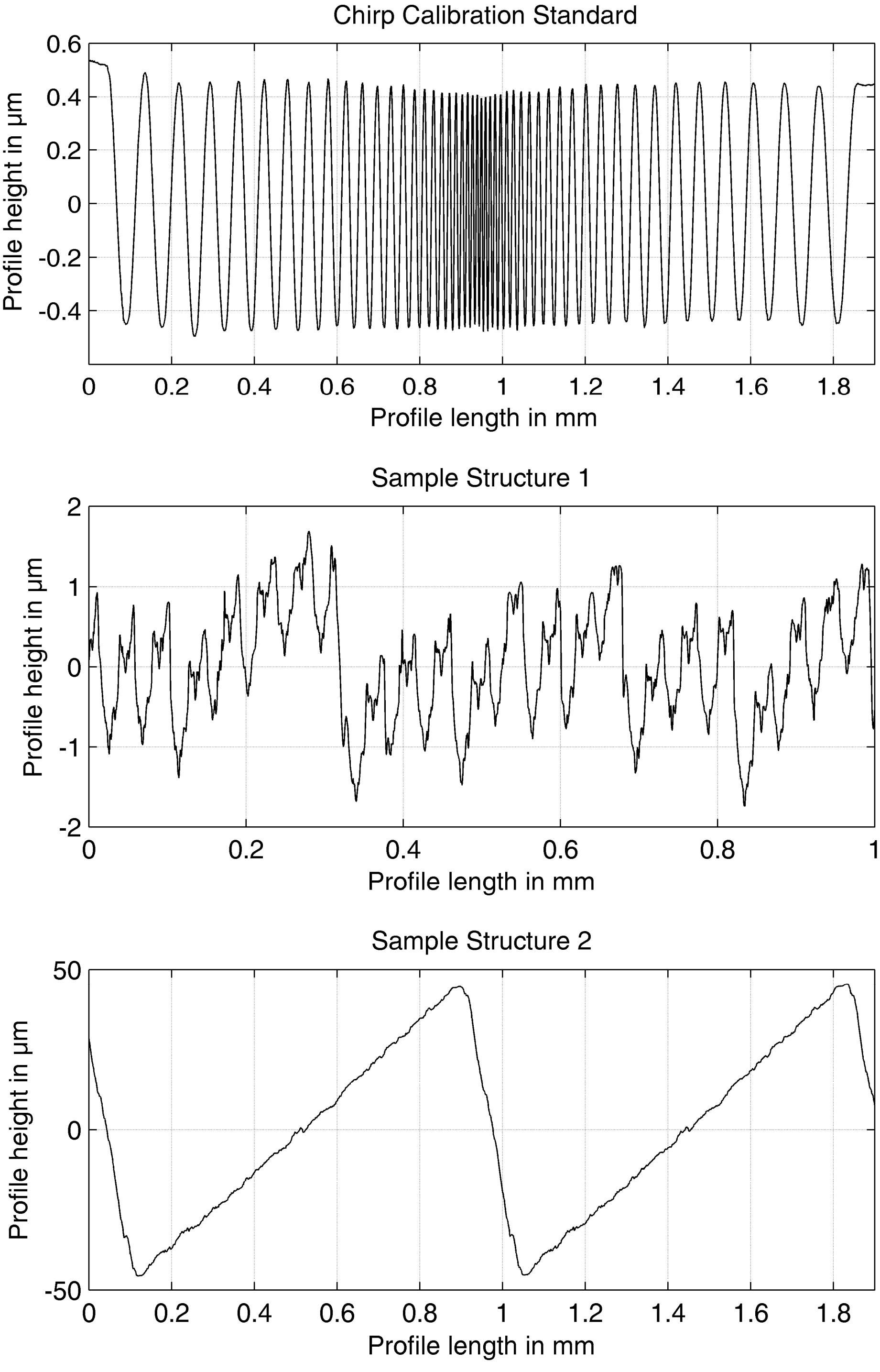

Figure 4: Profile scan of the three samples used to characterize the stylus profiler

5.3.1 Reproducibility

An important characteristic of the profiler is the reproducibility of its measured profiles. All measurements were carried out with a measuring force of 0.75 mN and were repeated 20 times. The measuring velocity was varied in three steps (20 µm/s, 50 µm/s and 100 µm/s) as it was expected to have a significant impact on the results. While scan speeds of several mm/s are possible, relatively slow measuring velocities have been chosen for these first tests to avoid damage of the profiler and the samples.

From the measured data, the arithmetic average of the absolute profile height deviations from the mean line, Ra, was calculated according to [7] as:

$$Ra = \frac{1}{l}\int_0^l |Z(x)|dx$$

l is the length of the measured profile and Z the profile height deviations from the mean line. The presented measurements do not meet the standards for measurements of the roughness of technical surfaces, especially regarding the measured profile lengths. Nevertheless, by calculating *Ra* information about the stability of roughness measurements can be obtained. Due to the averaging involved into calculation of *Ra* a low statistical spread of the values was expected. The results are listed in table 1. For all the measurement velocities and all three samples, *Ra* (mean value from 20 measurements) as well as the standard deviation of *Ra,* (named *Std. Ra* in the table, from 20 repetitions) was calculated. It can be seen, that slightly different values for *Ra* were obtained at different measuring velocities. They stay all in the range of ± 1 nm however. The standard deviation is never larger than 0.3 nm, for all samples and measuring velocities.

A more detailed insight into the capability of the profiler can be gained by taking a direct look at the reproducibility of the measured profiles. Every profile was measured 20 times. This means that for every point on the profile 20 height values were measured. Ideally these values should be all the same. As a measure for their variation, the standard deviation for every point on the profile was calculated. This value is not constant over the length of the profile. Figure 5 shows the measured profile of the chirp standard (top) and below the calculated standard deviation of the measured profile height. It can be seen, that the deviations of the measured profile height shows a periodic behavior that correlates with the periodic structure of the chirp standard. The variation of the measured profile height rises whenever the stylus tip measures on a falling edge.

Table 1: Reproducibility of profile scans

Scan speed		Chirp Standard	Sample 1	Sample 2
20 µm/s	Ra	0.3085 µm	0.5789 µm	23.242 µm
	Std. Ra	0.3 nm	0.1 nm	0.3 nm
	Std. Profile	0.8 nm	4.7 nm	6 nm
50 µm/s	Ra	0.3076 µm	0.5793 µm	23.243 µm
	Std. Ra	0.2 nm	0.1 nm	0.1 nm
	Std. Profile	0.6 nm	2.4 nm	5 nm
100 µm/s	Ra.	0.3071 µm	0.5795 µm	23.243 µm
	Std. Ra	0.1 nm	0.1 nm	0.2 nm
	Std. Profile	1.1 nm	2.9 nm	7 nm

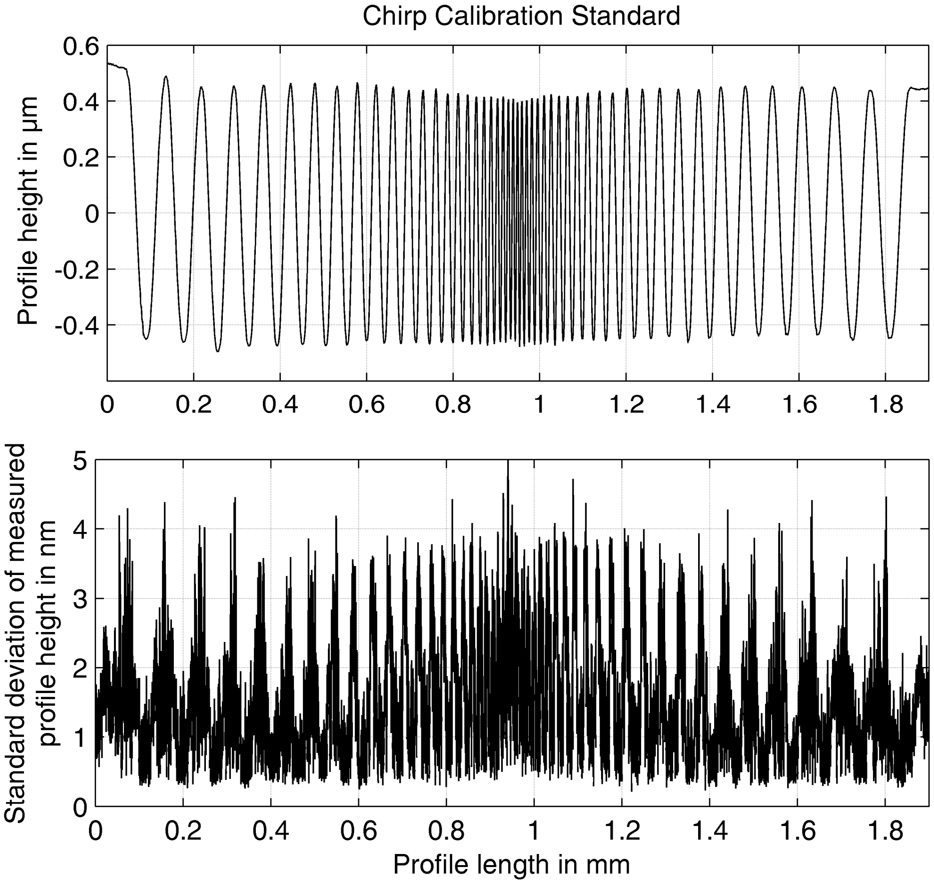

Figure 5: Profile of the chirp standard (top) and the calculated standard deviation for every point on the profile for 20 measurements (bottom)

It is assumed, that this effect is caused by stick-slip between the stylus tip and the surface, further investigations are needed however.

Table 1 lists the results for the measurements of all samples and all measuring velocities. The values *Std. Profile* are the mean standard uncertainties of the measured profile height. The results show that the reproducibility of a measured profile is mainly influenced by the structure of the profile itself. The measurements of the chirp structure, with its defined sinusoidal profile shows by far the best reproducibility (about 1 nm) in comparison to the two samples with a more random structure and sharper peaks (up to 5 nm standard deviation). A significant relation between the deviation of the height data and the scan speed is not noticeable.

5.3.2 Deviations of the contact force

The moving stage of the NMM-1 follows during profile scans the sample surface to keep the deflection of the stylus always at its setpoint of 0.75 mN measuring force. Though the changes of the deflection of the stylus are minimized, there are still deviations due to the limited dynamics of the positioning stage of the NMM. This leads to fluctuations of the measuring force, depending on the surface structure of the sample and the measuring velocity. This problem is inherent to the design of the profiler. For this reason the deviations of the measuring force have been calculated to identify possible problems.

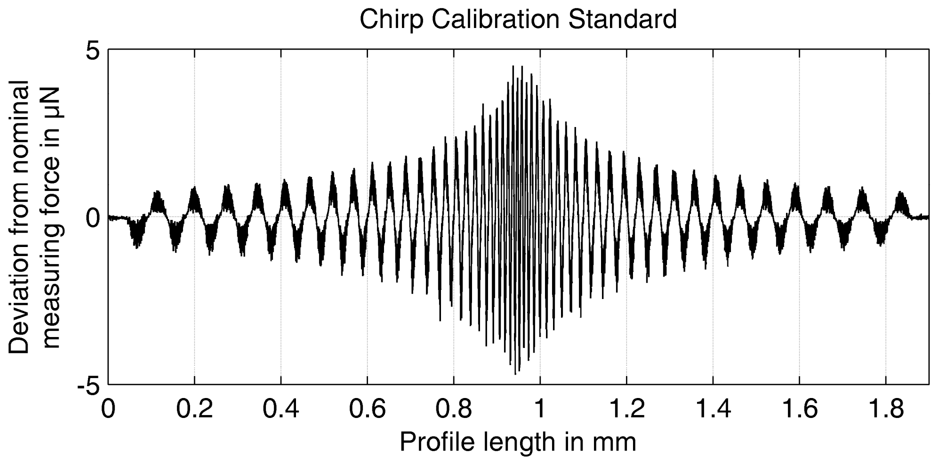

Figure 6: Deviations from the nominal measuring force of 0.75 mN during a scan of the chirp standard with 100 µm/s.

Figure 6 shows the measuring data for a profile scan of the chirp standard. It can be seen, that the variation of the measuring force gets bigger with the larger slope angles of the structure near its center, but stays below 5 µN at all times.

Table 2 shows all results. These were calculated from the same measurement data as used in section 5.3.1. The table lists the mean standard deviation of the measuring force *Std.* ΔF as well as the maximum deviation ΔF_{max}. The values for ΔF_{max} are especially important, as the surface can suffer plastic deformation if the contact force gets too high. (As reported in [8] even the nominal measuring force of 0.75 mN already produces scratches on most surfaces.) As to be expected, the values rise with the surface roughness of the sample and higher scan speeds. With a maximum of 17.3 µN for sample 2 at 100 µm/s, the measuring force does never differ more than 2.3% from the nominal value.

5.3.3 Tilt of the stylus

Due to friction, the measuring motion applies a force on the stylus tip in the opposite direction of the movement. As the flexure guide of the profiler has a high but limited stiffness in this direction, the stylus will be tilted. This will change the position of the stylus tip on the surface. It will not affect roughness measurements but any measuring application where the exact lateral position of two or more scan lines is important such as form or 2D-measurements. To obtain information about the movement of the stylus tip, all profiles have been measured in a forward and backward motion.

Table 2: Deviation of the measuring force and movement of the stylus tip.

Scan speed		Chirp Standard	Sample 1	Sample 2
20 µm/s	ΔF_{max}	1.5 µN	4.7 µN	14.6 µN
	Std. ΔF	0.17 µN	0.39 µN	1 µN
	$\Delta X_{StylusTip}$	0.15 µm	0.18 µm	0 µm
50 µm/s	ΔF_{max}	2.7 µN	7.8 µN	17.3 µN
	Std. ΔF	0.39 µN	0.85 µN	2.1 µN
	$\Delta X_{StylusTip}$	3.8 µm	1.7 µm	0 µm
100 µm/s	ΔF_{max}	4.7 µN	17 µN	17.3 µN
	Std. ΔF	0.71 µN	1.5 µN	3.8 µN
	$\Delta X_{StylusTip}$	3.8 µm	1.8 µm	1.4 µm

If the stylus tip is tilted, there will be an offset between the profiles in direction of the scan motion. A cross correlation was performed to calculate the gap. The results, as listed in table 2 as $\Delta X_{StylusTip}$, show that the tilt of the stylus depends on the surface structure as well as the scan speed. With a stylus tip displacement of up to 3.8 µm (chirp standard, 50 µm/s) it has a significant impact that needs to be taken into account. Further investigations of how to minimize this effect will be carried out in the future.

6. CONCLUSIONS AND OUTLOOK

A compact tactile stylus profiler, as a part of a multi-sensor concept was designed and integrated in the nano measuring machine NMM-1. Numerous repeated measurements of different profiles have been performed with an reproducibility of a few nanometers. Ongoing works will be concentrated on the optimisation of the flexure guide to reduce the tilt of the stylus as well as on the athermal design of the profiler by use of low expansion materials.
Measurements of certified standards as well as comparisons with other sensor systems need to be carried out in order to determine the uncertainty of the system.

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