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Non-contact, automated adjustment procedure for capacitive displacement sensors

Lars Daul[1,*], **Jin Tao**[2], **Ingo Busch**[1], **Ludger Koenders**[1], **Rudolf Meeß**[1] and **Helmut Wolff**[1]

[1] Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, Braunschweig, Germany
[2] University of Shanghai for Science and Technology (USST), Yangpu District, Shanghai, People's Republic of China

E-mail: lars.daul@ptb.de

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Abstract

Capacitive sensors enable non-contact displacement measurements in the micrometer range with sub-nanometer resolution. To achieve this, a proper alignment of capacitive sensors is necessary. In this work, a non-contact, automated and intrinsic adjustment procedure is presented which is based on determining the extrema of slope error and nonlinearity. After the final adjustment step, the remaining tilt is less than 1.5 mrad. A measurement routine is used to evaluate the adjustment procedure by applying tilt around the final adjustment position and measuring the global slope error and the global nonlinearity. The combination of adjustment procedure and measurement routine enables the investigation of capacitive displacement sensors with higher accuracy in order to establish a comprehensive uncertainty budget and to explore improvements in capacitive sensor technology.

Keywords: capacitive sensors, displacement measurements, slope error, nonlinearity, adjustment

(Some figures may appear in color only in the online journal)

1. Introduction

Capacitive sensors have long been an integral part of machine manufacturing and dimensional metrology [1, 2]. They are used in many applications for position determination due to their compactness, long-term stability, high measuring speed, and robustness against environmental influences [3]. Through calibration, measurement deviations can be reduced [4].

In a capacitive displacement measurement, the object being monitored is moved towards a fixed electrode called the probe. If the object under investigation is itself electrically conductive, it can be used as a counter electrode called the target; otherwise, the target must be mounted. Together, the probe and target form a capacitor [5]. For the measurement of small displacements with a resolution in the sub-nanometer range, the plate distance between the electrodes is changed and the displacement converted into an electrical signal using measurement electronics such as an AC bridge [6, 7].

In an ideal plate capacitor, the electric field is constant between the electrodes and zero elsewhere. Boundary effects and stray capacitances are therefore neglected. As such, the inverse of the electrical capacitance is directly proportional to the distance between the plates. Such simplifications, however, cannot be applied to real-world parallel-plate capacitors. At the edges, the electric field lines are no longer parallel, and fringing fields exist around the electrodes which lead to additional stray capacitances [8, 9]. These deviations from the ideal

* Author to whom any correspondence should be addressed.

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result in a slope deviation between the actual and the measured displacement, which is called the slope error. It is for this reason that capacitive sensors need to be calibrated [10]. This is done in a linear manner over the displacement range.

During displacement, however, nonlinearity effects—i.e. deviations from the linear calibration behavior—need to be taken into account. A simple measure of nonlinearity is the maximum of the residuals between the measured values and a straight line connecting the measured values at the first and the last distance. This is the so-called end point nonlinearity [5].

To reduce the influence of edge effects, the electrodes of capacitive displacement sensors are usually surrounded by a guard ring. The active electrode and the guard ring are electrically isolated from each other. A passive guard ring is kept on the ground potential and shields the active electrodes from interfering signals. However, since an active guard ring has the same electrical potential as the associated active electrode, the electric field lines at the edge of the active electrode are less distorted, and the slope error and nonlinearity of the displacement measurement are reduced by a factor of approximately ten [7].

The influence of the geometric properties of the electrodes of a capacitive sensor, such as the width of the dielectric gap between the active electrode and the guard ring, has been studied primarily using FEM simulations [10, 11]. The influence of surface topography deviations, waviness and roughness, has become increasingly important for the analysis of the uncertainty budget of capacitive displacement sensors [12–15]. Furthermore, a real sensor's surface is not equipotential [16]; i.e. the work function varies locally due to grain boundaries, local material differences, or contamination [17]. These variations cause patch potentials, which create an additional electrostatic force between two metal plates [18].

To verify the results of the FEM study and to investigate the influence of surface form deviation and patch potentials, all other influencing variables must be minor by comparison. In addition to the influence of the measurement electronics [19] and environmental factors such as humidity [5], the tilt of the electrodes in particular has a significant effect on capacitive displacement measurement [20]. For this reason, an adjustment procedure is developed in this work that enables the investigation of sensor properties without the additional influence of tilt.

In the 1st step, the effect of tilt on the slope error and nonlinearity is simulated. Next, an experiment similar to that described by Downs *et al* is set up, which is based on the results of a previous FEM study [10, 21]. The electrodes of a capacitive sensor are manufactured by ultra-precision diamond turning at PTB's scientific instrumentation department and a nanopositioning stage is used to move the target. A differential plane mirror interferometer (DPMI) serves as a reference for the displacement measurements. The change in the plate distance during displacement is measured by electronics from the PI company.

The key challenge in this experiment is to avoid the influence of the tilt between the inner surfaces of the probe and target. The adjustment method must fulfill the following criteria:

- High reproducibility,
- No influence on electric field lines between the electrodes,
- Contactless,
- Simple enough to enable measurements with many different sensors,
- Automated and
- Low cost.

Based on the FEM simulation, a method has been developed that fulfills these criteria. It consists of an intrinsic pre-alignment procedure combined with an adjustment procedure i.e. validated by a measurement routine.

This method allows the experimental investigation of the influence of sensor properties on capacitive displacement measurements without the interfering effect of tilt. Moreover, this adjustment procedure can be used in industrial applications to return capacitive sensors to their original factory calibration.

2. Simulation of tilt influence

To investigate the influence of tilt on slope error and nonlinearity, displacement measurements are simulated using COMSOL Multiphysics version 5.4 and performed as described in a previous study [10].

Two cylinders, probe and target, form the capacitive sensor. Their geometry corresponds to the geometry of real capacitive sensors. The probe and target each have a guard ring, separated by a gap of 40 µm in width. The capacitive sensor is placed in a surrounding sphere. The material aluminum 6063-T83 is assigned to the electrodes and air to the surrounding sphere. Dirichlet boundary conditions are set, according to which the probe and its guard ring have an electrical potential of 1 V and the target and its guard ring of 0 V. Infinite boundary conditions are assigned to the surrounding sphere such that the influence of its finite radius on the simulation result can be neglected. The Comsol algorithm is used for the meshing.

For the simulation of a capacitive displacement measurement, the capacitances are calculated for ten plate distances in the range of 30 µm and 80 µm using the rotational symmetry of the geometry. The ideal relationship between the capacitance and the plate distance in combination with the geometry is used to convert the simulated capacitance values into plate distances. The simulated plate distances are plotted over the real plate distances and normalized. The slope error is determined as the difference between the last plate distance and the last calculated value of the plate distance. The endpoint nonlinearity is the maximum residual between the calculated plate distances and a straight line connecting the first and the last calculated plate distance.

Ten displacement measurements are simulated with various tilt angles ranging from 0.17 mrad to 1.92 mrad. The correlation of slope error and nonlinearity to tilt is shown in figure 1.

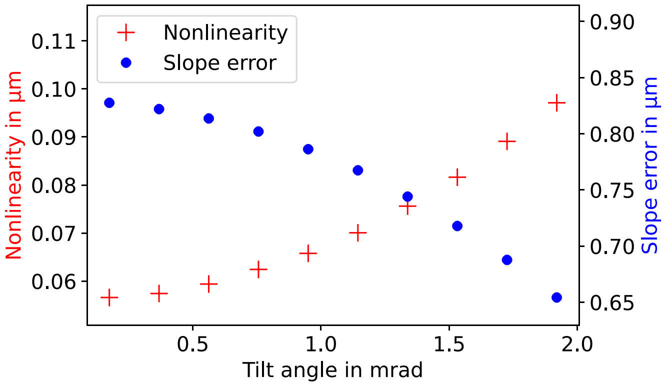

Figure 1. Result of a 3D FEM simulation. Ten displacement measurements were simulated with tilt angles between probe and target ranging from 0.17 mrad to 1.92 mrad. Slope error and nonlinearity are plotted against tilt angle. As the tilt increases, slope error decreases and nonlinearity increases.

Where the probe and target are parallel, the slope error has a maximum of 0.828 µm and the nonlinearity has a minimum of 0.057 µm. The simulation settings and parameters are listed in the appendix in tables 1 and 2.

To illustrate the influence of tilt on the electric field lines, the results of a 2D FEM simulation of a parallel-plate capacitor are presented in figure 2. In case (a), the probe and target are parallel. In the center of the capacitor, the field lines are undisturbed and parallel. At the edges, the distortion of the field lines is symmetric. With increasing tilt (b), the field lines in the center of the capacitor are disturbed and the distortion of the field lines at the edges becomes more asymmetric. For this reason, nonlinearity increases along with increasing tilt. At the same time, the sensitivity of the inverse capacitance with respect to the plate distance rises, causing the slope error to decrease.

3. Experimental setup

Figure 3 includes a sketch and a photograph of the measurement setup. The central elements consist of the cylindrical PTB-made probe and target electrodes that together form a capacitive sensor. They are manufactured as described in the work of Zhao *et al* [22], with the aluminum alloy RSA 905 from RSP Technology used as the electrode material. The height of both electrodes is 5 mm.

The diameter of the active surface of the probe is 6 mm, that of its guard ring 12 mm. The width of the dielectric gap between the active surface of the probe and its guard ring is 64 µm. The target is 9 mm in diameter, while its guard ring has an outer diameter of 17 mm. Both electrodes should be carefully positioned centrically to allow any deviations from the ideal, centric position to be neglected due to the size ratios. The surface roughness of the probe is $R_a = 93$ nm and the surface roughness of the target is $R_a = 74$ nm.

The probe is fixed in a kinematic rotation mirror mount (supplied by Thorlabs), which is attached to a positioning stage. It can be moved in the *x*- and *y*-directions and can be tilted in pitch and yaw using picomotor actuators (New Focus 8301NF). The probe can also roll. However, because of the rotationally symmetrical surface structure of the electrodes used in this work, the influence of roll can be neglected. Positioning in the *z*-direction is also not necessary, due to the difference in size between the probe and target. The target is fixed on an *x,y*-nanopositioning stage (PI P-621.2CD), which has two internal capacitive sensors for the closed-loop mode with a resolution of 0.1 nm and a maximum displacement range in the *x*- and *y*-directions of 100 µm.

The displacement of the PI nanopositioning stage is also measured with the DPMI by measuring the movement of a mirror mounted on the stage in relation to a fixed U-mirror. A Heydemann correction is used to calculate the distance from the phase shift [23] and a frequency-stabilized helium-neon laser (SIOS) with a wavelength of 633 nm is used as the light source. The nonlinearity of the interferometer is less than 100 pm, which is sufficient for investigating the nonlinearity of capacitive sensors [24].

A mirror is fixed on the mirror mount behind the probe. The change in probe tilt is measured via the mirror using a two-axis autocollimator (Möller-Wedel Optical Elcomat 2000). The autocollimator has a resolution of 0.0002 mrad and a repeatability of 0.001 mrad. The entire measurement setup is located on an active vibration damping table.

The E727 capacitive measuring bridge from PI is used to read out the signal from the capacitive sensor. The maximum measurable displacement range of this PI system is 50 µm. It is calibrated by the manufacturer using their own capacitive sensors. Owing to differences between the geometries of the PTB and PI electrodes and between the electrical contacts, deviations from the calibration condition will occur. This means that the specifications given in the data sheet will not be achieved if the PTB sensor is used without being recalibrated. The configuration of the electronics, however, is not changed during the experiments, so comparable investigations are possible.

4. Pre-alignment

For displacement measurement, the capacitive sensor and the interferometer need to be aligned. The 1st step is to mount the probe and target onto the stages. Here it is imperative not to damage the electrode's measuring surfaces (inner cylinder). Damage to the guard ring will have no measurable effects.

The probe and target must be brought together close enough for the capacitance to be within the measuring range of the PI electronics. This is done by focusing LED light on the slit between the electrodes: probe and target are brought together to a distance of approximately 0.5 mm. An LED is positioned behind the capacitive sensor. The light that shines through the slit between probe and target depends on the tilt of the electrodes: the more parallel the electrodes are, the less light is shaded and the amount of light that shines through increases.

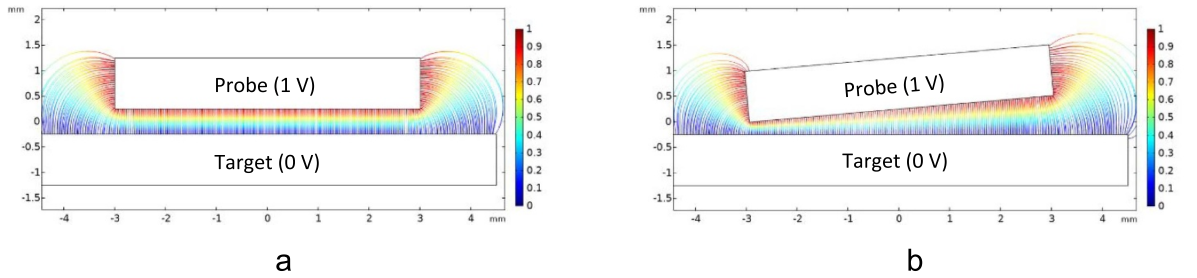

Figure 2. Result of a 2D FEM simulation. Influence of tilt on the electric field lines of a parallel-plate capacitor. (a) Probe and target are parallel. (b) Probe is tilted with respect to target.

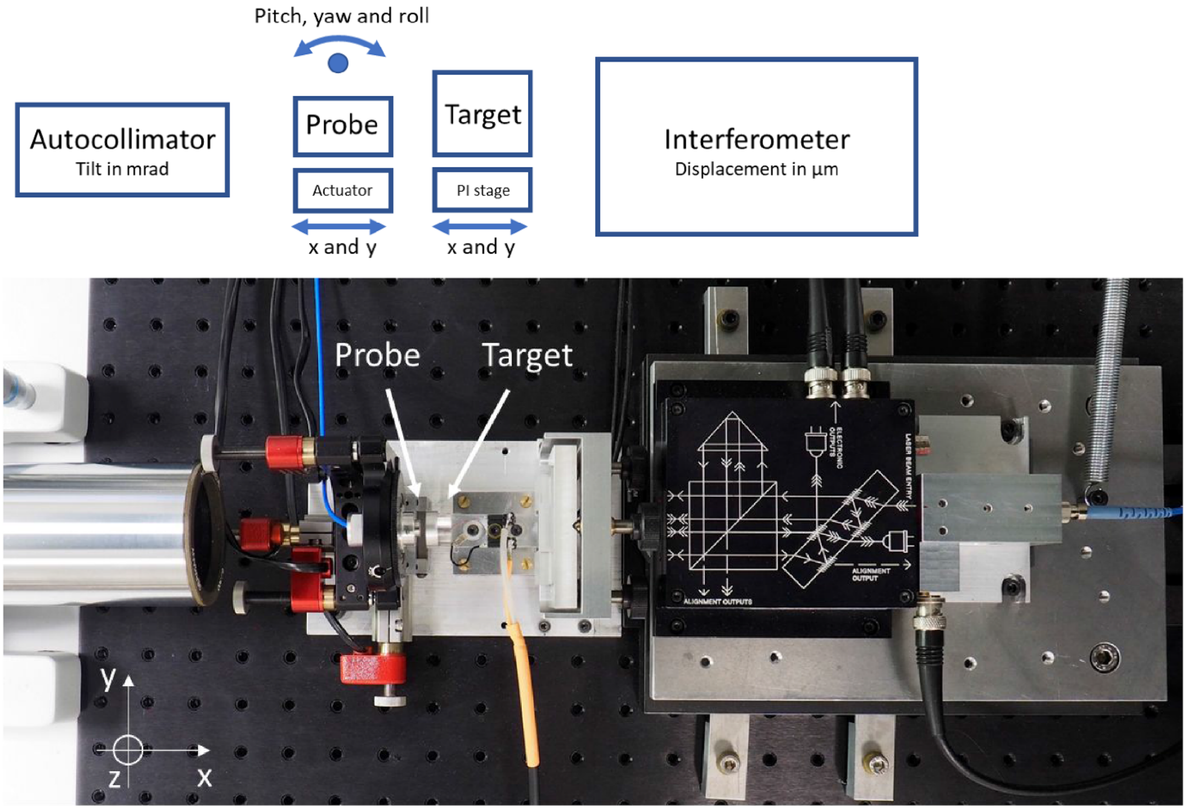

Figure 3. Experimental setup for the measurement of capacitive displacement sensors with respect to an optical interferometer system. The autocollimator (left) is used to measure the change of tilt of the probe. The probe is fixed in a kinematic rotation mirror mount to which four picomotor actuators are attached. The probe can thus be moved in x,y-pitch and yaw. The target is mounted on a 100 µm × 100 µm x,y-nanopositioning stage, which is used for displacement measurements. A DPMI is used as reference for the displacement of the target.

In this way, sufficient parallelism of the electrodes can be achieved in 90% of cases, placing the capacitance of the capacitor within the measuring range of the PI system and ensuring that the electrodes do not touch when approaching the probe to the target.

Should the probe nonetheless touch the target, the nanopositioning stage will be moved back by a few nanometers, with this movement detected using the interferometer. Because the diameter of the probe is smaller than the diameter of the target, a collision of the two will only cause the edge of the probe's guard ring to touch the surface of the target. As the resulting indentation in the target is well removed from the active surface of the probe, the influence on the capacitive displacement measurement can be neglected.

In the next step of pre-alignment, it must be ensured that a non-contact displacement of the target by 50 µm is possible and that the change in distance can be detected by the electronics. The maximum plate distance displayed by the PI E727 electronics is 49.6 µm. Picomotor actuators are used to move the probe closer to the target, while the interferometer serves to check if the electrodes are touching. The probe is tilted by the picomotor actuators in pitch and yaw until a distance of less than −1 µm is displayed by the electronics and no contact with the target is detected. The picomotor actuators then move the probe away from the target in the *x*-direction until a distance of 49 µm is measured by the electronics. A non-contact capacitive displacement measurement of 50 µm is now possible.

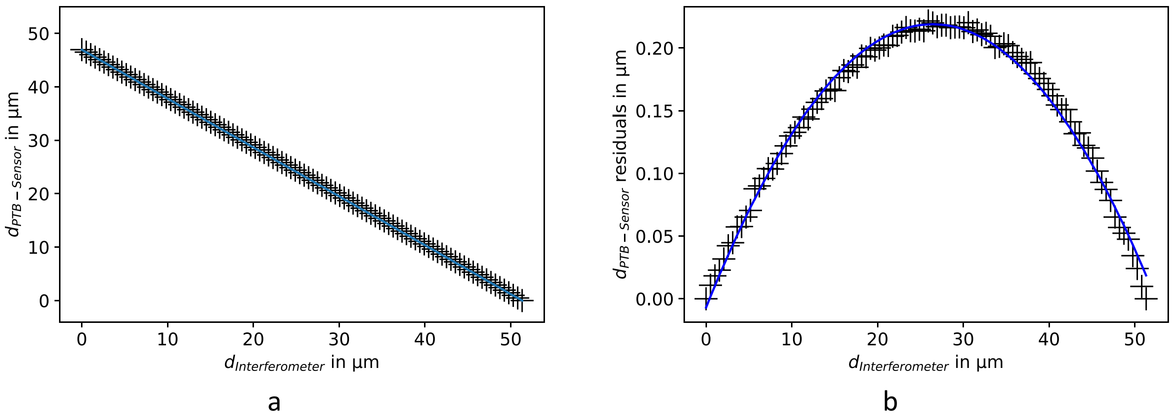

Figure 4. Displacement measurement with the PI electronics. (a) The plate distance of the capacitive sensor as measured with the PI system is plotted against the interferometer measurements. The slope error is 4.16 µm. (b) The endpoint nonlinearity is 0.22 µm.

5. Displacement measurement: slope error and nonlinearity

In a displacement measurement, a voltage is applied to the nanopositioning stage on which the target is mounted. The voltage is increased from 0 V to 5 V in steps of 0.01 V and then reduced in identical steps back to 0 V. The displacement is measured using the interferometer. The average displacement for 20 measurements is 51.59 µm with a standard deviation of 6 nm. There is no measurable difference between forward and backward displacements. The autocollimator is used to verify that the tilting of the nanopositioning stage during movement is less than ±5 µrad, which can be neglected.

In the forward direction, the target is moved away from the interferometer towards the probe. The result of the displacement measurement is presented in figure 4. The measurement range is from 48.99 µm to 1.56 µm. The measured distance is 47.43 µm. The slope error, i.e. the difference between the distance measured with the interferometer and that measured by the capacitive sensor and the electronics, is 4.16 µm, and the endpoint nonlinearity is 0.22 µm. For nine repeated displacement measurements, the standard deviation of the slope error is 8 nm and of the nonlinearity 2 nm. This single measurement on its own, performed directly after pre-alignment, does not provide any information about the tilt between the electrodes.

6. Development of the adjustment procedure

As stated above, the adjustment process must be reproducible, contactless and automatable. It is furthermore important that the electric field lines of the capacitive sensor not be disturbed by any additional components used to measure the tilt. An intrinsic adjustment procedure must therefore be developed i.e. simple enough to allow large numbers of experiments to be performed with capacitive sensors having different geometries and surface properties.

The FEM simulation shows that the slope error and the nonlinearity of the displacement measurement contain information about the tilt of the electrodes. The result of the FEM simulation is therefore first verified experimentally and it is used as the basis for developing an adjustment procedure that fulfills the requirements outlined above.

6.1. Defined tilt steps

For the experimental investigation of tilt influence and for the development of the adjustment procedure, the probe must be tilted with respect to the target in a defined and repeatable manner. The actual tilting is done by means of 8301NF picomotor actuators, which are slip-stick motors.

An external feedback system is required for repeatable movements. In this work, the position of the capacitive sensor is used as the feedback for the tilting and movement performed by the picomotor actuators. When the probe is tilted in pitch or yaw, the effective plate distance becomes either larger or smaller depending on the direction. Given the relationship between capacitance and plate distance, the tilt in one axis changes the distance signal measured by the electronics and this signal serves as the feedback for the tilt. This means that the probe is moved by the picomotor actuator towards the target in the x-direction until the electronics indicate a value of 49 µm. This value is close to the end of the measuring range of the electronics and enables a large, controlled movement. In the next step, the probe is tilted in one axis towards the target until the measured distance is reduced to 10 µm. Measurements with the interferometer indicate that the probe and target are not in contact.

Next, the probe is moved by the picomotor actuator in the x-direction away from the target until the measured distance returns to the initial value of 49 µm. Through this procedure, the probe is tilted about its center with respect to the target. For the opposite tilt direction on the same axis, the probe is first moved towards the target by the picomotor actuator in the x-direction until a distance of 10 µm is measured. Finally, the probe is tilted away from the target until measurement again shows a distance of 49 µm.

Although the probe is moved to the distance value initially measured, the actual distance changes. The capacitance,

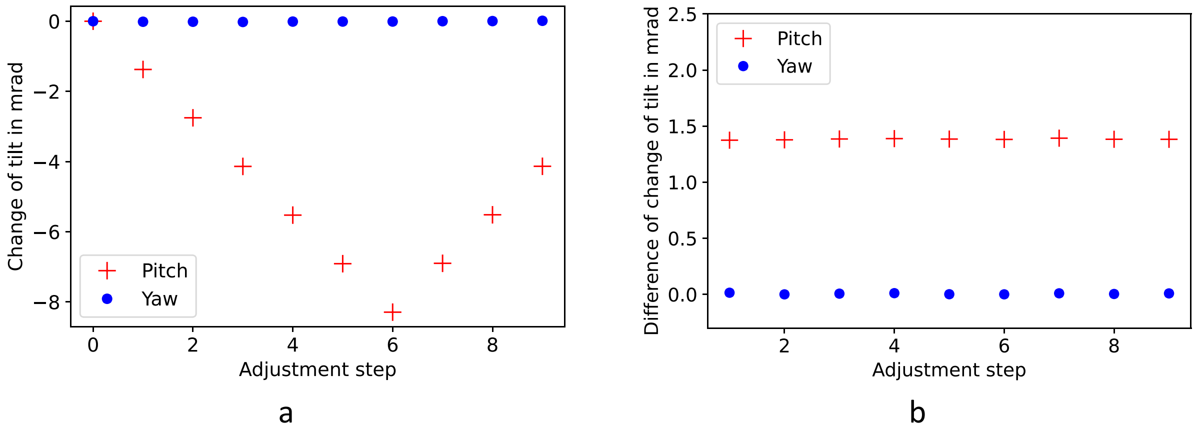

Figure 5. Change of tilt of the probe when tilted in pitch. (a) The change of tilt in pitch and in yaw is plotted against the adjustment steps. From step 6, the tilt direction is changed from positive pitch to negative pitch. (b) Difference of change of tilt as a function of tilt steps.

however, remains the same, and this is converted into a distance value by the electronics. As such, the tilt is controlled with respect to the capacitance and not to the plate distance.

To verify the repeatability of these tilt steps, the probe is tilted in pitch ten times. The autocollimator is used to measure the change in tilt of the mirror behind the probe, which corresponds to the change in tilt of the inner surface of the probe. In figure 5(a), the changes in the tilt in the primary axis (pitch) and the secondary axis (yaw) are plotted against the number of tilt steps. Up to tilt step 6, the probe is tilted in the negative direction. Subsequently, it is tilted back in the positive direction. Figure 5(b) shows the magnitudes of the differences between tilt steps. In pitch, the average change of tilt is 1.382 mrad with a standard deviation of 0.005 mrad. The change of tilt in yaw is negligible. Furthermore, there is no measurable deviation in the difference between the tilt steps when the tilt direction is changed. The repeatability of these non-contact, closed-loop tilt steps is sufficient for the adjustment of the capacitive sensor.

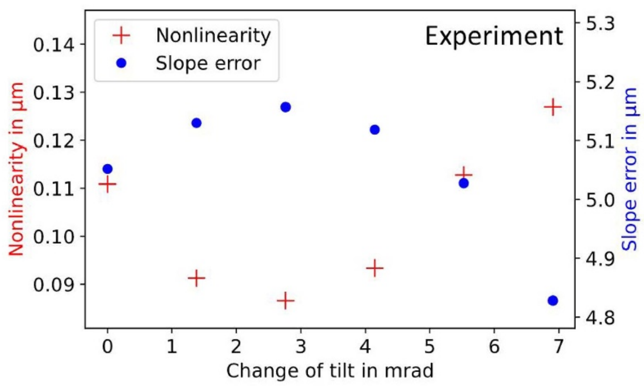

Figure 6. Experimental investigation of the influence of tilt between probe and target on slope error and nonlinearity in pitch. Six displacement measurements were taken. Slope errors and nonlinearities are plotted as a function of change of tilt. Initially, slope error increases and nonlinearity decreases until both reach a local extremum. Upon further tilting, slope error drops again while nonlinearity rises.

6.2. Experimental investigation of tilt influence

For the experimental investigation of the influence of tilt, the probe and target were first pre-aligned. The 1st displacement measurement resulted in a slope error of 5.052 µm and a nonlinearity of 0.111 µm. In the next step, the probe was tilted in pitch towards the target, as described previously. The displacement measurement was repeated using the nanopositioning stage. This procedure was repeated five more times and the results are shown in figure 6, where the slope errors and nonlinearities are plotted against the tilt.

In the 1st two tilt steps, the slope error increases and the nonlinearity decreases. After the 3rd tilt step, the slope error drops again while the nonlinearity rises. As in the FEM simulation, the slope error has a maximum and the nonlinearity has a minimum. The maximum slope error here is 5.157 µm while the minimum nonlinearity is 0.087 µm.

In the simulation, the slope error had its maximum and the nonlinearity its minimum when the probe and target were parallel. This allows the conclusion that the probe and target in the experiment were parallel in the vicinity of the 3rd displacement measurement in the pitch axis. The results of the experimental investigation qualitatively coincide with the results of the FEM simulation, and this correlation was used to develop the adjustment procedure.

6.3. Adjustment procedure

The relationship between slope error, nonlinearity and tilt was used to develop the adjustment procedure. The complete adjustment process is shown in figure 7. A displacement measurement is performed at each adjustment step and the slope errors and nonlinearities determined and plotted against the adjustment steps. The parallel alignment of the electrodes is achieved when the slope error is maximized and nonlinearity minimized by changing the pitch and yaw.

The 1st displacement measurement is performed and the slope error and nonlinearity determined (step 1). The probe is tilted in one direction of pitch. The slope error seen in step 2 is smaller and the nonlinearity larger than in step 1, indicating

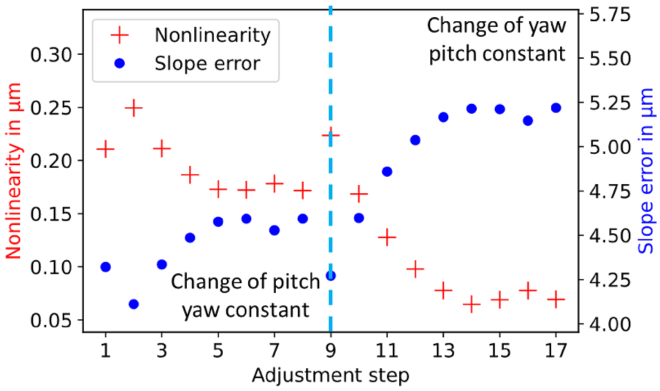

Figure 7. Adjustment procedure based on maximizing slope error and minimizing nonlinearity. Slope errors and nonlinearities are plotted against the adjustment steps. From steps 1 to 7 the probe is tilted in pitch and from steps 8 to 17 in yaw. In both directions, the parallel point is exceeded. After tilting one step back, the adjustment is completed.

that the tilt direction is incorrect. By tilting in the opposite direction of pitch, the slope error increases and the nonlinearity decreases. In step 6, the respective extrema for slope error and nonlinearity are exceeded. After one tilt step back in the opposite direction, the adjustment of the pitch is completed. This process is then repeated for yaw. In the end, the tilt between the probe and target is less than 1.5 mrad. The slope error is increased by 949 nm and the nonlinearity reduced by 164 nm. For six repeated adjustment algorithms, the standard deviation of the final position is 17 nm for the slope error and 5 nm for the nonlinearity.

This procedure was repeated with two other commercial electronic measuring systems (Andeen Hagerling AH2550A, Micro-Epsilon capaNCDT 6500). Quantitative comparison is difficult due to the fact that an in-house capacitive sensor was used. The differences, for example, in the geometry between the PTB sensor and the commercial sensors of the respective manufacturers lead to large differences in measurement performance. Nevertheless, the results are qualitatively consistent, and the adjustment procedure is therefore independent of the choice of electronics.

6.4. Non-calibrated vs calibrated measurement systems

The simulation and the experimental investigation are in qualitative agreement. When the probe and target are parallel, the slope error has a maximum and the nonlinearity has a minimum. However, in a calibrated measuring system, the measurement deviations are calibrated using a function, so that both slope error and nonlinearity approach a minimum when the tilt is reduced. This is demonstrated in figure 8 using a capacitive sensor system from Micro-Epsilon (ME electronics: capaNCDT6500, ME sensor: CSH1FL-CRm1.4) that was calibrated by the manufacturer.

The sensor was mounted and pre-aligned using the described procedure. A measured distance of 100 µm was chosen as the starting distance for displacement measurements of 50 µm. In these measurements, changing the tilt caused the

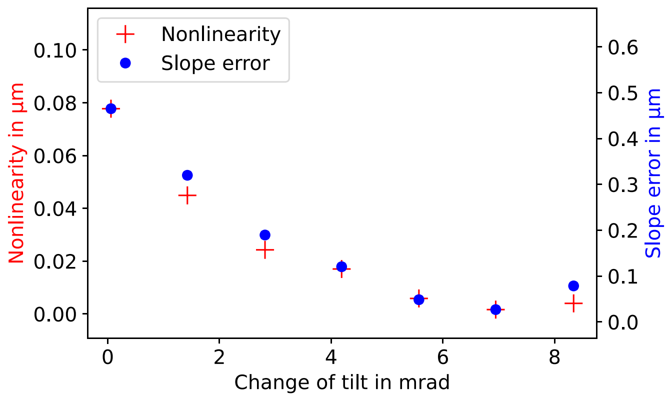

Figure 8. Influence of tilt on the Micro-Epsilon capacitive sensor system. The slope error and the nonlinearity are positively correlated.

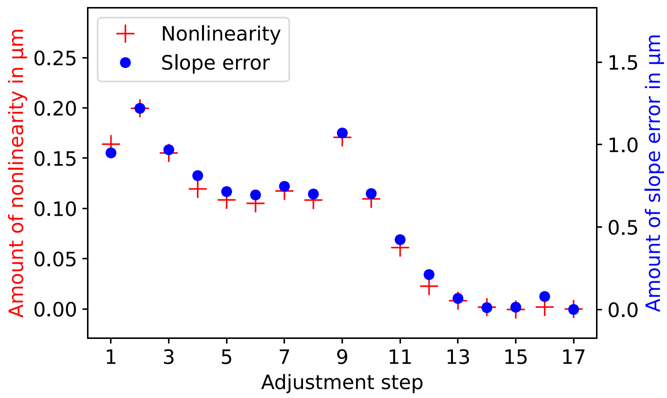

Figure 9. Correction of the adjustment curve of figure 7 assuming that the capacitive sensor is parallel at adjustment step 17 and that slope error and nonlinearity are 0 nm. This corresponds to a calibrated sensor where slope error and nonlinearity approach a minimum.

slope error and nonlinearity to approach a minimum, i.e. they were positively correlated.

In the case of a calibrated sensor, the adjustment procedure approximates the value corrected by the calibration function, resulting in slope error and nonlinearity that are close to zero. If the adjustment curve presented above (figure 7) is also calibrated such that the slope error and nonlinearity are zero in the final adjustment position (step 17 in figure 7), the curve presented in figure 9 is obtained.

When adjusting capacitive sensors in experimental investigations, it must be discerned whether or not the system is calibrated. Normally, calibrated sensor systems are used in industrial applications. If the sensor is tilted, the calibrated state can be restored using the proposed intrinsic adjustment procedure. For non-calibrated systems, the relationship between slope error and tilt depends on the calibration function. In both cases, nonlinearity is minimized when the probe and target are parallel. Therefore, the endpoint nonlinearity is the appropriate quantity for evaluating the adjustment of capacitive sensors, despite the fact that the quantitative influence of tilt on slope error is greater than on nonlinearity.

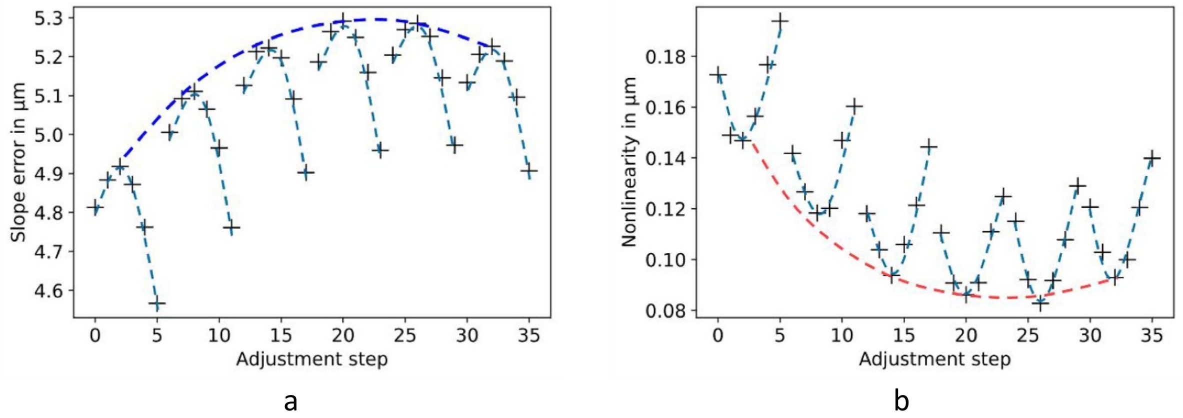

Figure 10. Result of a complete measurement routine. Slope errors (a) and nonlinearities (b) are plotted against the adjustment steps. A displacement measurement is taken at each step. Local maxima for slope error and local minima for nonlinearity are obtained.

Because phenomenological calibration uses higher-order polynomials, the model-based background of the influencing variables is lost. The measurement electronics become black boxes, and if misalignment occurs, the capacitive sensor systems have to be recalibrated externally. Model-based calibration enables in-house correction using, for e.g. the adjustment procedure presented above, and is therefore preferred from a metrological standpoint.

7. Evaluation of adjustment procedure by measurement routine

The adjustment procedure is a good method for reducing the tilt between the probe and the target to less than 1.5 mrad. For further reduction, the step size of the individual adjustment steps can be decreased, but at the cost of extending the duration of the adjustment. To evaluate whether the optimum of the adjustment procedure is local or global, a measurement routine has been developed. The results are shown in figure 10.

After the adjustment procedure, the probe is de-adjusted by three adjustment steps in pitch and accordingly in yaw. In the next step, the probe is tilted back six steps in pitch, and the slope errors and nonlinearities are determined at each step by means of displacement measurements. This results in the 1st local slope error maximum and the 1st local nonlinearity minimum, as depicted in the 1st parabola up to adjustment step 5 in figures 10(a) and (b). This process is repeated five more times. In this way, the probe is tilted around the final position of the adjustment procedure. In figure 11, the local slope error maxima and the local nonlinearity minima are plotted in a diagram against the adjustment steps in yaw.

A parabola is then fitted through the local extrema, with the maximum of the parabola of the local slope errors representing the global slope error, and the minimum of the parabola of the local nonlinearities indicating the global nonlinearity. For the capacitive sensor investigated here, the global slope error was 5.304 µm and the global nonlinearity was 0.085 µm. For five repeated measurement routines using the same probe and target, the standard deviation for the global slope error was 12 nm and the standard deviation for the global nonlinearity was 4 nm.

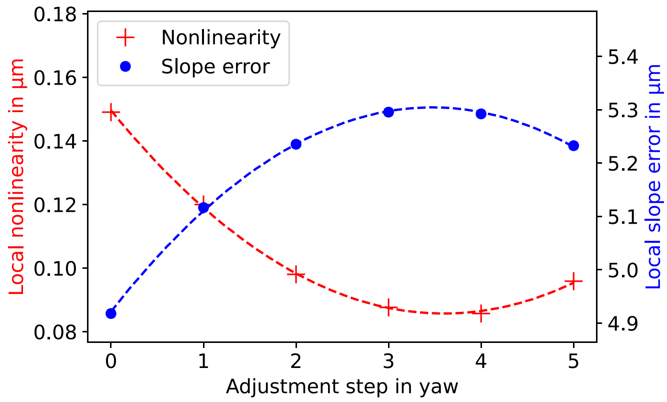

Figure 11. Final result of the measurement routine. The local maxima of slope error and the local minima of nonlinearity are plotted against the adjustment steps in yaw. The maximum of the parabolic fit through the local slope errors is the global slope error and the minimum of the parabolic fit through the local nonlinearities is the global nonlinearity.

The global slope error and global nonlinearity represent residual variations from an ideal displacement measurement, with their magnitudes now depending solely on the properties of the given sensor and on the internal correction function of the electronics employed. As such, keeping this correction function constant allows to investigate the influence of the sensor properties on the capacitive displacement measurement.

This measurement routine furthermore makes it possible to evaluate the tilt and identify which commercial sensors have been calibrated. The extremum is exactly 0 nm when a perfectly parallel capacitive sensor is calibrated. A difference between the position of the extremum and the zero crossing indicates a tilt during calibration.

8. Conclusion

In this study, a combination of intrinsic pre-alignment and an adjustment procedure based on FEM simulation has been developed which enables a reproducible, contactless, and automated minimization of tilt in capacitive sensor systems. In the case of an uncalibrated sensor, the probe and the target are parallel when the slope error is at maximum and the nonlinearity at minimum. In a calibrated sensor system, measurement deviations are corrected using a calibration function, so the slope error and nonlinearity are close to zero. For these sensors, the adjustment process is applied to approach these zero values. The final tilt is less than 1.5 mrad and can be further reduced by applying smaller adjustment steps. The procedure is independent of the selected measuring electronics.

In the measurement routine, the probe is tilted around the final adjustment position. It has been demonstrated that the global slope error and global nonlinearity are achieved using the adjustment procedure. Furthermore, this measurement routine can be used to check the tilt under which the capacitive sensor was calibrated. It additionally allows the investigation of the influence of sensor properties, such as sensor geometry or patch potentials, on the capacitive displacement measurement without the influence of tilt, thereby providing a broader, model-based foundation for calibration and enabling improvements in sensor technology.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflicts of interest

The authors declare no conflict of interest.

Appendix

Table 1. COMSOL simulation settings.

COMSOL version	5.4
Solver	Iterative, nonlinear method: automatic (Newton)
Mesh type	Tetrahedral
Mesh element size	Maximum: 0.4 mm, minimum: 0.004 mm
Maximum element growth rate	1.3
Curvature factor	0.2
Resolution of narrow regions	8

Table 2. COMSOL simulation parameters.

Radius surrounding sphere	25 mm
Probe radius	3 mm
Probe guard ring radius	6 mm
Probe gap width	40 μm
Target radius	4.5 mm
Target guard ring radius	8.5 mm
Target gap width	40 μm
Material surrounding sphere	Air
Material electrodes	Aluminum 6063-T83
Boundary conditions electrodes	Probe 1 V, target 0 V
Boundary conditions sphere	Two layers (0.5 mm) infinite boundary conditions
Parameter sweep plate distance	(30 μm, 80 μm)
Parameter sweep tilt angle probe	(0.17 mrad, 1.92 mrad)

ORCID iDs

Lars Daul https://orcid.org/0000-0003-1531-5673
Ludger Koenders https://orcid.org/0000-0002-0673-6743
Rudolf Meeß https://orcid.org/0000-0002-9009-8034

References

[1] Jones R V 1967 The measurement and control of small displacements *Phys. Bull.* **18** 325
[2] Revesz G 1956 Capacitive measurements of high sensitivity and their applications to industrial testing and control *IRE Trans. Ind. Electron.* **PGIE-3** 32–39
[3] Hicks T R and Atherton P D 1997 *The Nanopositioning Book* (Torquay, Torbay: Queensgate Instruments)
[4] Haitjema H 2020 The calibration of displacement sensors *Sensors* **20** 584
[5] Nyce D S 2004 *Linear Position Sensors: Theory and Application* (NY: Wiley)
[6] Heerens W C and Vermeulen F C 1975 Capacitance of Kelvin guard-ring capacitors with modified edge geometry *J. Appl. Phys.* **46** 2486–90
[7] Heerens W C 1982 Basic principles in designing highly reliable multi-terminal capacitor sensors and performance of some laboratory test models *Sens. Actuators* **3** 137–48
[8] Hosseini M, Zhu G and Peter Y-A 2007 A new model of fringing capacitance and its application to the control of parallel-plate electrostatic micro actuators (arXiv: 0711.3335)
[9] Parker G W 2002 Electric field outside a parallel plate capacitor *Am. J. Phys.* **70** 502–7
[10] Daul L, Jin T, Busch I and Koenders L 2021 Influence of geometric properties of capacitive sensors on slope error and nonlinearity of displacement measurements *Sensors* **21** 4270
[11] Lanyi S 1998 Analysis of linearity errors of inverse capacitance position sensors *Meas. Sci. Technol.* **9** 1757
[12] Nihtianov S 2008 Capacitive sensor surface quality considerations when measuring sub-nanometer displacement *Proc. Electronics-ET'08* pp 15–18
[13] Murugarjan A and Samuel G L 2011 Measurement, modeling and evaluation of surface parameter using capacitive-sensor-based measurement system *Metrol. Meas. Syst.* **18** 403–18
[14] Smith P, Vallance R and Marsh E R 2005 Correcting capacitive displacement measurements in metrology applications with cylindrical artifacts *Precis. Eng.* **29** 324–35
[15] Smith P T Jr 2007 Capacitance metrology of curved surfaces: study and characterization of a novel probe design *PhD Thesis* University of Kentucky

[16] Kim W J, Sushkov D D A R and Lamoreaux S K 2010 Surface contact potential patches and Casimir force measurements *Phys. Rev.* A **81** 022505

[17] Camp J B, Darling T W and Brown R E 1992 Effect of crystallites on surface potential variations of Au and graphite *J. Appl. Phys.* **71** 783–5

[18] Speake C C and Trenkel C 2003 Forces between conducting surfaces due to spatial variations of surface potential *Phys. Rev. Lett.* **90** 160403

[19] Lanyi S and Hrskovic M 2001 Linearization of inverse-capacitance-based displacement transducers *Meas. Sci. Technol.* **12** 77

[20] Patla B R 2012 Small angle approximation for non-parallel plate capacitors with applications in experimental gravitation (arXiv:1208.2984)

[21] DownsM J and Nunn J W 1998 Verification of the sub-nanometric capability of an NPL differential plane mirror interferometer with a capacitance probe *Meas. Sci. Technol.* **9** 1437

[22] Xianbin Z, Physikalisch-Techische Bundesanstalt, Braunschweig (Germany) Abt. Fertigungsmesstechnik 1998 Scanning probe microscope with high resolution capacitive transducers *Dissertation*

[23] Heydemann P L M 1981 Determination and correction of quadrature fringe measurement errors in interferometers *Appl. Opt.* **20** 3382–4

[24] Yacoot A and Downs M J 2000 The use of x-ray interferometry to investigate the linearity of the NPL differential plane mirror optical interferometer *Meas. Sci. Technol.* **11** 1126