3 DOF POSITIONING OF A CAPACITIVE MEASUREMENT ELECTRODE USING THE THERMAL SLIDER ACTUATOR

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INTRODUCTION

In the semiconductor industry there is a need for measuring the relative displacement between machine parts, such as optical elements, with sub-nanometer uncertainty and within a typical motion range of several micrometers. This combination makes capacitive measurement with parallel electrodes a suitable and relatively cheap sensor principle. The sensor sensitivity is dependent on the distance between and the relative orientation (the tilt angle) of the electrodes [1]. In order to achieve sufficient sensitivity and linearity, the measurement electrode must be at 10±0.1 micrometers distance from the target electrode and parallel within a few milliradians. Obtaining this during sensor installation is not feasible and manual adjustment afterward is not possible due to inaccessibility. An actuator incorporated in the sensor could however automatically position the electrode, using itself as a sensor. Both distance and tilt angles are measured by the measurement electrode, which has three segments. The gain error due to tilt of the electrode is in this case not relevant, because the required measurement accuracy during alignment is significantly lower than during the final measurements and the positioning goal is always zero tilt-angle.

To perform sufficiently accurate measurements, the position stability *after alignment* must, despite the motion capability, still be better than 200 pm over a time span of 2 minutes. The *thermal slider actuator* depicted in Figure 1 was developed at Delft University of Technology for this purpose. It combines the motion capability with a good mechanical stability.

This paper will first introduce the thermal slider actuator and explain the basic working principle. Then the actuation cycles for motion in 3 Degrees of Freedom (DoF) are discussed, and the control algorithm that selects thermal sequences is show and implemented in an experimental setup. Finally a 3-DoF positioning experiment shows the actuator's positioning capabilities.

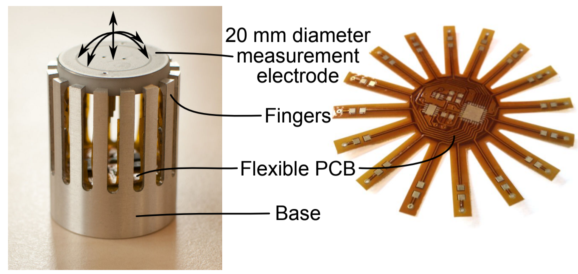
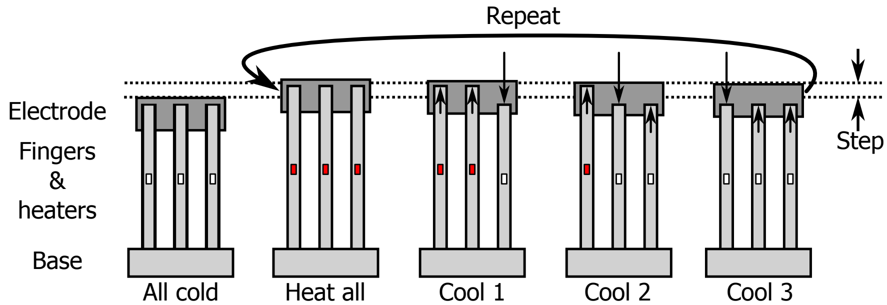


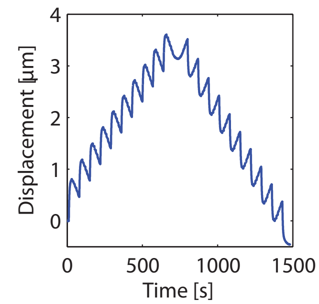
FIGURE 1. An aluminium thermal slider demonstrator (left) with 16 fingers that can be heated individually from the inside, by electrical resistors on the flexible PCB (right).

THE THERMAL SLIDER ACTUATOR

The thermal slider actuator is a low-cost USB-powered and USB-controlled actuator that automatically positions, aligns and calibrates the capacitive sensor. It is a part of an integrated sensor system design that also includes a novel capacitance to digital converter that uses a zoom-in capacitor to achieve a fast high-resolution measurement and a resistive reference for sufficient electronic readout stability [2]. The mechanical part typically consists of a base and more than 10 fingers, machined out of one part. The actuator is electrically connected to the PC, only during the alignment procedure and is entirely passive during the measurement afterward. Then, the fingers stably clamp the electrode while the environment is milliKelvin stable. This results in required mechanical stability. During alignment the electrode is displaced by active heating and passive cooling of the fingers in a specific sequence, causing a displacement that is maintained when heat is no longer applied to the system. Heat is applied to the fingers by electrical resistors, in Figure 1 on the inside, electrically connected by a flexible PCB. On this PCB a micro-controller receives serial actuation commands from a computer, and a switch controls the current through the heating resistors. Closed loop temperature control is not required as this process is sufficiently reproducible. This keeps both the mechanical and the electrical part of the actuator simple.



(a) The principle of actuation in one dimension. First all fingers heat up. When a single finger cools down, it will slide over the electrode surface due to the thermally induced preload, while the electrode is clamped by the other fingers and remains roughly stationary. Each iteration therefore results in a net displacement. The vertical arrows indicate contact shear forces. The positioning process is relatively slow, but it has to be performed only during installation.



(b) Displacement of the sensor electrode as a function of time, showing 10 upwards and 10 downwards thermal cycles. For downward motion the cycle is inverted in time. Temperature differences are typically 2 Kelvin.

FIGURE 2. Working principle of the thermal actuation cycle.

The working principle of the actuator is explained using the one-dimensional case shown in Figure 2a, this will be expanded to cycle variations for one translational and two rotational degrees of freedom further on. The basic cycle for a positive displacement starts by heating, and thus expanding, all fingers simultaneously. This moves the electrode upwards. Next the fingers are cooled down successively. This causes the cooling fingers to slide over the electrode surface, while the electrode is held into place by a larger number of fingers. In the figure, one finger is sliding and two are locking the position. The only electrode-displacement during this step, is due to *elastic* deformation in the locking fingers. At the end of the cycle a net step has been made and all fingers are at their initial temperatures. The cycle can therefore be repeated. The motion that typically results from a series of such cycles is shown in Figure 2b.

The performance of the thermal slider, both to actuate *and* to fixate, is strongly determined by its thermal and tribological properties. The thermal behavior is relatively straightforward, but the friction between a finger and the electrode required closer investigation. In [3] it was shown that in contacts and motions typical for the thermal slider actuator, the relative motion is governed by creep, and no stick-slip effects are present. Relative motion starts when the contact force becomes larger than a threshold, but sudden displacement (such as stick slip jumps) due to internal stresses and external loads do not occur.

In order to use the thermal slider actuator for the intended positioning and alignment task, i.e. to bring the measurement electrode to the required distance from the target electrode and align them, the measurement electrode must be actuated in 3 DoF. The thermal cycles that can be used for that will be discussed in the next Section.

3 DOF ACTUATION

The translational motion of which the principle was shown before, can be extrapolated directly to the 16-finger stepper shown in Figure 1: heating all fingers and cooling them successively. [4] showed however that simultaneous actuation of groups results in a more efficient motion: each cycle results in a smaller motion, but requires less time. Actuation in 2 and 4 groups of 8 respectively 4 fingers will be used.

A pure tilt motion is defined as a rotation of the electrode around an axis parallel to, and in the middle of the electrode surface, shown as the dashed line in Figure 3. This means that the one side of the electrode is moving upwards and the other side downwards. It can therefore be actuated with a positive and a negative step-cycle on either sides of the electrode as is shown in Figure 3.

There are two important cycle variables that influence the tilt motion. First the step size is influenced by heating power, which was shown in [4] for the translational motion as well. This variable will not be considered further as it is not supported by the current setup in order to keep the

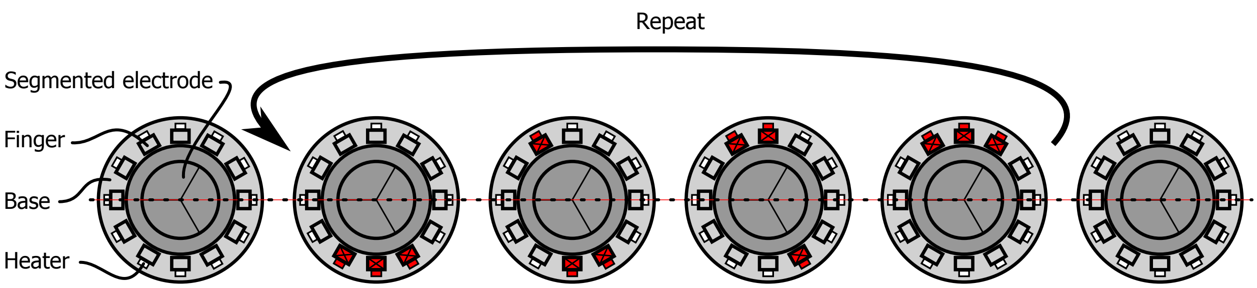


FIGURE 3. The steps of a simplified thermal tilt-cycle in a top view of a 12 finger thermal slider actuator. Fingers that are heated are indicated with an 'X'. Only 6 fingers (2 groups of 3 stepfingers) are used for actuation. The dotted line represents the axis of rotation. Note that simultaneous actions, heating a finger on one side and cooling one on the other side, occur exactly opposite of each other with respect to the tilt-axis to limit tilt motion in other directions than the required one.

actuator and the control simple. The other variable is the number of fingers that participate. Figure 4 shows a qualitative summary of some experimental results, in which the number of fingers that is used for tilt actuation is varied. Tilt-steps in groups of 4 to 8 fingers on each side, the maximum on the 16 finger actuator, were measured. Using a less than 5 fingers leads to unpredictable motions. The top graph shows that the step-size when using 6, 7 or 8 fingers does not change significantly, which is explained by the fact that fingers close to the axis of rotation contribute relatively little to the tilt motion. The time consumed by cycles using less fingers is smaller and therefore the motion speed of these cycles is larger, as is shown in the lower graph of Figure 4. Using a low number of fingers does however come at a cost: the boxes in the top graph show that the variation in the step-size is larger when a small number of fingers is actuated.

The step-cycles described so far ideally perform a pure tilt and a pure translation motion. To efficiently move the measurement electrode in a 3-dimensional space, tilt and translation combination cycles are defined: a motion-cycle is then only performed on one side of the actuator.

To use the actuator for closed loop positioning, a cycle must be selected from the described set of available cycles. This set contains a selection of cycles that lead to a relatively fast and reliable motion. Note that all tilt cycles can be performed in a number of directions equal to the number of fingers. The selection procedure is discussed in the following Section.

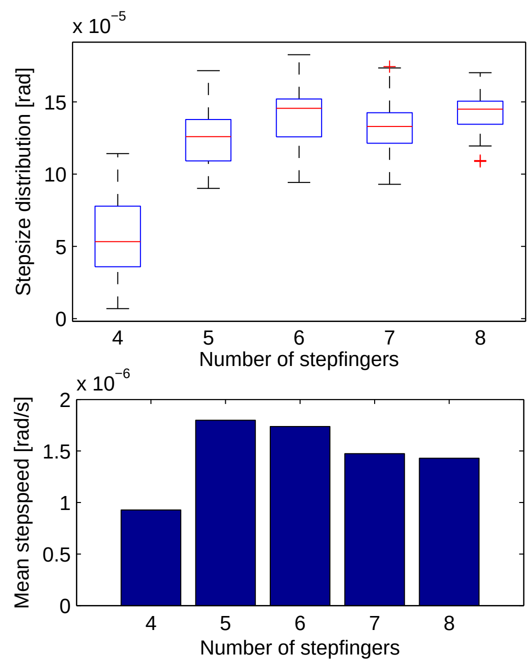


FIGURE 4. Experimental results that show the influence of the number of stepfingers used on each side of the thermal slider on the resulting tilt motion for a 16 finger thermal slider actuator. The fingers were heated with 0.3 W each.

POSITION CONTROL

The positioning procedure consists of two stages: during coarse positioning the selection procedure selects cycles that move the electrode to its position goal in a reasonably efficient way. When the positioning goal is close compared to the actuator step size, the fine positioning algorithm waits for the actuator to approach thermal equilibrium and then selects a cycle that will reduce the position error. This procedure is repeated until the error cannot be reduced further.

It is important to note that the actuator motion is both discrete in time and discrete in space. Only the displacement after a cycle matters, and the motion magnitude of a cycle cannot be arbitrarily close to zero, due to the nonlinear behavior of friction and the absence of heating power control. For the cycle selection, information about the resulting motion of the cycles is required. This can be estimated by a simplified model, shown by the dashed lines in Figure 5. The used relations assume an equal normal force and static friction coefficient at all fingers. These variables may however vary significantly, dependent on the manufacturing process. Measurements, such as indicated by the solid lines in Figure 5, can then be used to give more accurate information and thus allow more accurate position control.

The cycle information can be gathered in a number of different ways. First of all the estimated motions can be used to start coarse positioning. During this process the resulting displacement of the different cycles are monitored. This information is then used for further positioning. Not all different cycles are however used during coarse positioning and the missing data has to be estimated based on what is available. Reaching the final position may therefore take more cycles and thus more time. Alternatively an actuator calibration, in which the electrode motion of all cycles is measured can be performed before the coarse positioning.

When the calibration data is known, the most suitable cycle can be selected. This is the cycle that results in the smallest estimated position error after the cycle. Only during coarse positioning the estimated actuator displacement is scaled using the cycle time to achieve a relatively fast motion. For this selection the position error and the actuator motions have to be compared, which is not directly possible because they have units of both meters and radians. In the computations angular dimensions are therefore scaled with an appropriate dimension. In this case the radius of the electrode was chosen as this makes the actuator motion steps in the different directions of comparable magnitude. This is illustrated in Figure 5, where the horizontal axis is scaled. In this scaled space the appropriate cycles are selected. Note that the scaling of these axis does influence the eventual actuator motion as a large angular scaling factor makes angular position errors contribute relatively much to the total position error.

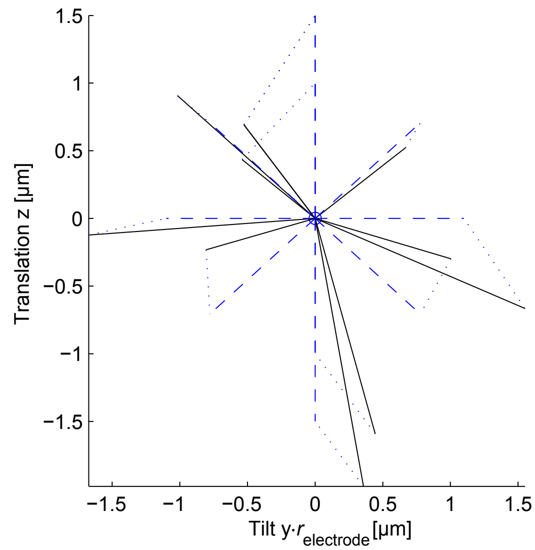


FIGURE 5. Thermal slider calibration for 8 motion directions in 2 dimensions. The dashed lines represent ideal, estimated motion steps, the solid lines represent measured actuator motions. The dotted lines connect the measurement with the corresponding ideal motion. Note that the tilt axes are scaled with the electrode radius of 11 mm in order to have the same units on all axes.

EXPERIMENTAL SETUP

The actuation and positioning principles described before are verified experimentally. The used experimental setup contains first of all the thermal slider actuator depicted in Figure 1. This actuator is manufactured of aluminium and the surface is anodized to provide an electrically insulating layer. The actuator is embedded in an aluminium block to provide a thermally stable base, see Figure 6, and is connected to a PC through a USB to serial convertor. The actuation commands are generated by a Matlab program. The speed of this program is not an issue as the timing of this system is not more critical than sev-

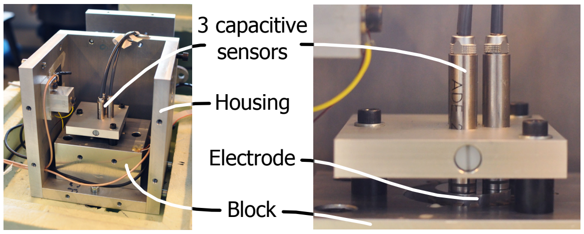


FIGURE 6. Pictures of the measurement setup. On the left the aluminium housing and the block that contains the actuator. On the right a detail of the capacitive displacement sensors on top of the steel electrode that is clamped by the actuator. The sensors are centered on a circle with radius 6 mm. The aluminium box was closed on all sides during measurements to reduce the influence of lab-temperature variations.

eral tenths of a second. In the final application, the tilt angles of the electrode are measured using a segmented electrode. In the experimental setup 3 coupled, commercially available and calibrated sensors from ADE, type 4810 with a measurement range of 50 μm are used. The maximum range for tilt-measurement is in the order of 5 mrad. Analog to digital conversion and readout in the computer was performed using the 16-bit convertors of a National Instruments USB-6211 interface. The noise on the signals is approximately 5 nm peak-peak for displacement and 5 μrad peak-peak for tilt. Position deviations due to lab temperature variation are in general within 40 nm per hour for displacements and within the noise level for tilt. The Matlab program converts the sensor signals to displacement and tilt signals and records the electrode position before and after each cycle to determine its relative motion.

EXPERIMENTAL RESULTS AND DISCUSSION

Two types of experiments were conducted with the described setup. First the actuator is characterized, then the positioning function is verified.

Actuator characterization

Before analyzing the motion cycles, the motion range is looked into. The expected maximum range of the actuator is significantly larger than the measurement range of the described setup. The translational motion of the actuator can be millimeters. Using an alternative setup, a laser beam bouncing of the electrode surface on a position sensitive device (PSD), it was shown that the tilt motion range is at least 50 mrad.

For sake of control simplicity it was decided to perform the actuator calibration before the start of positioning. The measured motion steps, like already shown in Figure 5, are therefore known before positioning. In order to obtain a reliable calibration all the selected cycles were repeatedly tested. This showed that the motion deviations of distinct instances of the same thermal cycle can be significant, differences up to 20% of the average step-size were observed on this specific actuator sample. These motion differences can be explained by the differences in pre-load in the fingers at the start of each cycle, also observed in the thermo-mechanical model of the actuator, and by friction irregularities.

Another non-ideality that was shown in the calibration measurements is that there are also significant differences between the ideal and the measured motion directions, shown as the differences between the solid and the dashed lines in Figure 5. These can be explained by variations in the normal force and friction parameters between the different fingers. These non-idealities are however detected in the calibration and because this information is used for position feedback, it is still possible to achieve sufficient positioning accuracy, as will be shown next.

Positioning

Figure 7 shows a measurement of closed loop positioning over a relatively small range. The feasible positioning accuracy of the actuator can be estimated by the magnitude of the used steps. The translations steps are approximately 1 μm and the tilt steps around 0.1 mrad, therefore the final position errors are expected to be smaller than these values. This was the case for the specific measurement shown in Figure 7 and in general for the other measurements performed. In the shown example the distance traveled is approximately 28 μm in displacement and 2.6 mrad in tilt, which took about 4800 s and 56 cycles. The actuator cycles that are selected by the algorithm are first pure tilt-cycles in varying directions, and several translational cycles. The final position is then reached using combined tilt and translation cycles as well. Note that the selected (type of) cycles are very much dependent on the required motion direction and the the set of actuator directions that is used.

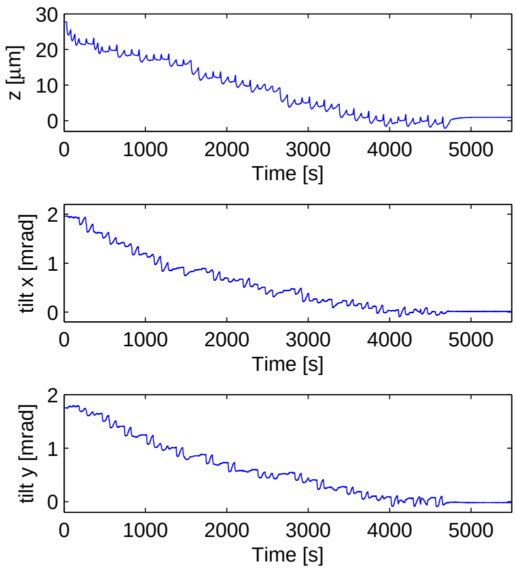


FIGURE 7. Measured tilt control to 0 displacement and 0 tilt in both directions. The initial position error is around 28 μm in translation and 2.6 mrad in tilt. The final a positioning error of 0.9 μm in translation and 23 μrad in tilt.

CONCLUSIONS AND FUTURE WORK

In the foregoing the thermal slider actuator, a mechanically and electrically simple actuator for positioning and aligning a capacitive measurement electrode with respect to a target electrode, has been presented. The thermal cycles for translation, tilt, and combinations thereof displace the measurement electrode in three degrees of freedom. Using a selection of the possible heating cycles that result in motions in the different directions, closed loop positioning of the measurement electrode in all 3 degrees of freedom was implemented on a thermal slider actuator measurement setup. The differences between model predicted and measured actuator motion can be significant, but by using a control algorithm that uses information about the real actuator obtained during a calibration step, positioning the electrode with final position errors smaller than the positioning resolutions of 1 μm and 0.1 mrad for translation and tilt respectively is achieved. This shows that the thermal slider actuator is a solution for positioning on the micrometer scale that is robust for imperfections.

The positioning resolution of the actuator is currently limited by the step-size caused by the thermal cycle. As the used steps are mainly selected to perform coarse and thus relatively fast positioning, their performance for fine positioning is suboptimal. Adding dedicated fine-positioning cycles will improve the positioning resolution. A next step can be made by lowering the input power to a point where the step size is smaller but still sufficiently reproducible. Finally the control algorithm can be improved, for instance by selecting a series of cycles that approach the positioning goal closer than the single step that is currently selected, by changing the balance between tilt and translation actuation and by including the cycle motion uncertainty in the cycle selection procedure. Based on earlier research and experiments, it is expected that these changes will further improve the positioning resolution with an order of magnitude, achieving the the positioning goals required for picometer resolution position measurement using the measurement electrode.

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