High-resolution capacitive sensor with integrated automatic alignment mechanism

A new concept has been developed that overcomes alignment problems in high-resolution capacitive sensors. This concept, called 'thermal stepper', is based on thermal actuation of clamping elements and allows automation of alignment procedures. A prototype of a self-aligning capacitive sensor head was realised and it was demonstrated to have sub-micrometer positioning accuracy and sub-nanometer long-term clamping stability.

• *Jeroen van Schieveen* •

In many high-precision systems relative position accuracy of key components is reaching the level of nanometers or even better. Mechanical solutions used to be sufficient when requirements were less stringent. High-stiffness constructions or use of special low-expansion materials enabled reduction of vibrations or deformations due to temperature variations to a tolerable level.
In cases when pure mechanical methods are not sufficient anymore, active compensation of the remaining position errors is a solution. Systems that perform this task rely on sensors to detect these residual displacements. In order to compensate sub-nanometer errors, their resolution should be high, in the order of tens of picometers. Next to this, the

Author's note

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stability should be at sub-nanometer level and especially when measuring vibrations, measurement speed must be high, in the order of several kHz.

Small-range, high-resolution measurements are typical applications for absolute sensors, such as capacitive sensors. However, for this type of sensors, resolution, speed and range are generally inversely related to each other. Although the measurement range for detection of vibrations or drift in geometry is in most cases small (<10 μm), the total range is much larger. Tolerances in fabrication and assembly of different parts in a machine can build up to several hundreds of micrometers. As the unknown initial position will have to be covered within the measurement range of the sensor, the total range has to be at least a few hundred micrometers.

This extension of the measurement range makes it difficult to achieve the combination of required very high resolution, range and speed with absolute sensors. Therefore, it is necessary to align the sensors after assembly of the complete machine. Manual alignment however is time consuming and for this the sensors need to be reachable. Alignment mechanisms make the system more complex and may decrease the mechanical stability of the system.
A capacitive sensor system that does not suffer from large fabrication and mounting tolerances could be used without time-consuming and costly alignment procedures. This would decrease installation time and overall machine costs.

Capacitive distance or proximity sensors

The capacitive distance sensor is based on a long known physical phenomenon; see Figure 1. Two conducting plates positioned parallel at a distance *d* from each other with overlap *A* form a capacitance *C*, which can be described by its geometric properties as follows:

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot A/d$$

In this equation ε_0 is the constant permittivity of vacuum ($8.85 \cdot 10^{-12}$ F/m), and ε_r is the relative permittivity of the medium in between the two plates or electrodes (~1 for air). It may be clear that changing either *A* or *d* results in a changing capacitance.

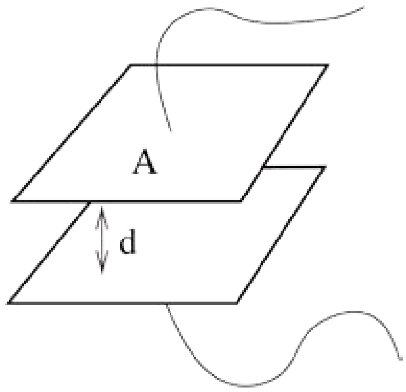


Figure 1. Basic principle of a capacitive distance sensor. Two parallel conducting surfaces with overlapping surface area *A* form a capacitor of which the value is dependent on the distance *d* and the medium with relative permittivity ε_r.

As capacitance can also be described in electrical properties charge (*Q*) and voltage (*V*) as $C = Q/V$, it is possible to convert the capacitance with an electronic system to e.g. an analog or digital electronic signal. When the overlap *A* is fixed and known, the output of such a system directly gives information about the electrode distance *d*.

Common capacitive read-out circuits provide an output signal that is related to the relative capacitance change, which means that the measured change is related to the absolute capacitance of the electrode structure. The signal-to-noise ratio or resolution of these read-out systems is limited. Depending on the speed, it varies between ~14 bits for fast measurements (up to tens of kHz) and 24 bits for slow measurements (~100 Hz).

What does this mean for the mechanical properties of the sensor head? The geometrical properties have to be chosen carefully to achieve the required resolution. To do this, we first take a look at the sensitivity of the parallel plate capacitor:

$$\delta C/\delta d = -\varepsilon_0 \cdot \varepsilon_r \cdot A/d^2$$

As the read-out circuit works with relative numbers, it is more logical to work with the relative sensitivity. This is obtained by dividing the equation above by the total capacitance:

$$\delta C/(C\ \delta d) = -1/d \text{ or } \delta C/C = -\delta d/d$$

It is clear that the sensitivity of the system is only determined by the absolute distance *d*.
Sub-nanometer resolution at reasonable speed (~10 kHz) is only possible on a very small distance. If we assume for example a resolution of 16-17 bits at the required speed,

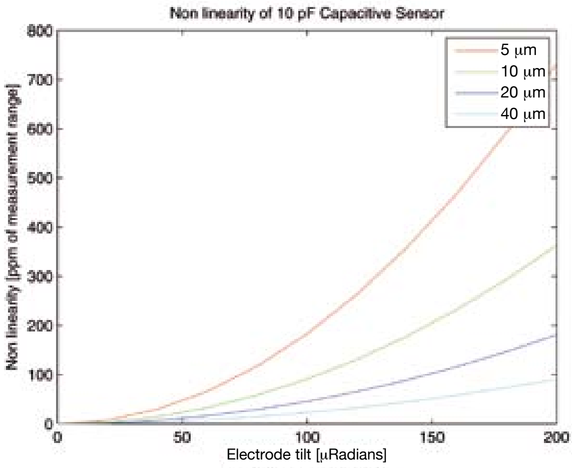


Figure 2. Non-linearity of a 10 pF capacitive sensor as a function of the tilt angle at different nominal distances.

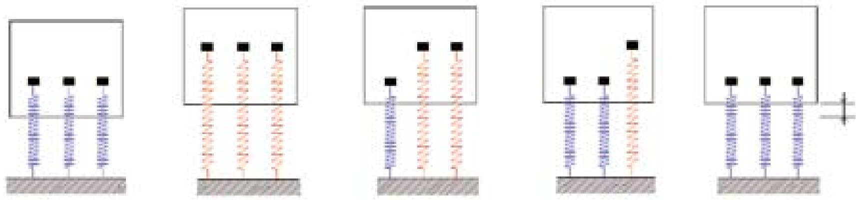


Figure 3. Operation principle of the thermal stepper system. A typical heating cycle consists of heating all three clamping elements at the same time and cooling them one after the other. Cooling down one of the elements means that this specific element will slip relative to the object and will shorten, while the object is held in place by the majority of the elements. The friction force of the cooling element will however cause a slight compression of the other elements. A typical step size for a 20 mm system takes about 30 seconds and is 1 μm/K.

the maximum distance for 100 picometer resolution can only be $100 \cdot 10^{-12} \cdot 2^{17} = \sim 10$ μm.

Alignment

Accurate placement of the sensor electrodes at the small initial distance cannot be achieved by only relying on fabrication tolerances and normal mounting procedures. Without precautions, the total error after mounting can easily be 50 μm or more. This may result in a too small distance, where the electrodes will touch and the sensor will not work properly, or in a too large distance, making the resolution of the measurement too small.
Mounting without alignment will result in non-parallel electrode surfaces and this deviation will affect the linearity of the sensor system and therefore introduces an error in the measurement. Figure 2 shows the resulting non-linearity error as a function of tilt angle for different nominal distances of the sensor electrodes for a sensor with a realistic nominal capacitance of 10 pF.

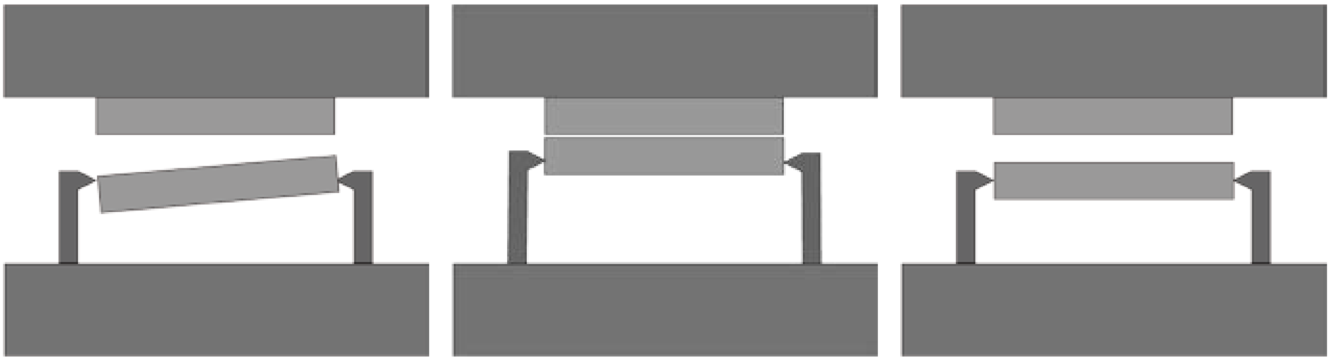
For a capacitive sensor with a nominal distance of 10 μm, it is easy to calculate that the maximum allowed tilt angle can only be 100 μrad when the error over a measurement range of 1 μm should remain sub-nanometer (100 pm). From the above it is clear that unstable mounting and alignment errors prevent a capacitive sensor system from operating properly. A new concept has been developed that overcomes alignment problems and enables the use of relatively cheap capacitive sensors in many applications in which they could not be applied until now.

Thermal stepper concept

The new concept for positioning has been named 'thermal stepper', after the typical stepping motion and thermal actuation. The system is based on a monolithic structure that uses a clamping force to hold the sensor electrode in place. Thermal actuation by heaters placed on this structure enables (re)positioning of the electrode.
In contrast to common thermal actuators, this system is able to produce a permanent displacement of the object after a thermal cycle, even if the heating power is switched off. This is achieved by applying heat during a cycle in such a way that the moving object slides relative to the clamping structure. Displacement in one direction is generated by first heating all elements at the same time and then cooling them one after the other. Figure 3 shows the working principle with a theoretical minimum of three clamping elements.

Displacement in the opposite direction is possible by an inverse cycle, in which the elements are heated in serial order and cooled all together. A consecutive combination of these thermal cycles results in a stepping motion of the object, enabling a large stroke of the system in the order of millimeters, in principle only limited by the available amount of time and the size of the mechanism.
Figure 4 shows how the proposed system can be realised. The round layout makes it ideal to align typically round sensor electrodes. Fabrication of the clamping structure out of one piece of material makes it possible to realise a very stable system, which is also far more simple than mechanisms made out of many different parts.

Figure 4. Possible construction of the clamping structure with the moveable electrode.



Phase 1:
Stepping motion moves one electrode towards the other, until they come into contact.

Phase 2:
Expansion of all clamping elements pushes the electrodes into a parallel position.

Phase 3:
Cooling down of all clamping elements retracts one electrode over a predefined distance.

Figure 5. Alignment procedure with the thermally actuated positioning system.

Procedure

Alignment of the sensor electrodes always starts with decreasing the large initial distance of up to 100 μm by moving the electrodes towards each other. The exact alignment can be done in two different ways. A first possibility is to move the electrode further, as depicted in Figure 5. A final heating step in which all elements are heated to the same temperature, pushes the electrodes into contact and makes them become parallel. Cooling down of all elements afterwards ensures a retraction over a fixed distance while the electrodes stay parallel within acceptable limits because all clamping elements are designed to behave identical.

A second option is to divide the measurement electrode into different segments, which allows measuring not only distance, but also tilt. Controlling the heating in such a way that elements on opposite sides move in different directions makes it possible to rotate or tilt the electrode. Combined with the normal linear movement this will result in an active control of both distance and two tilt angles, which makes the system capable of three-degree-of-freedom positioning.

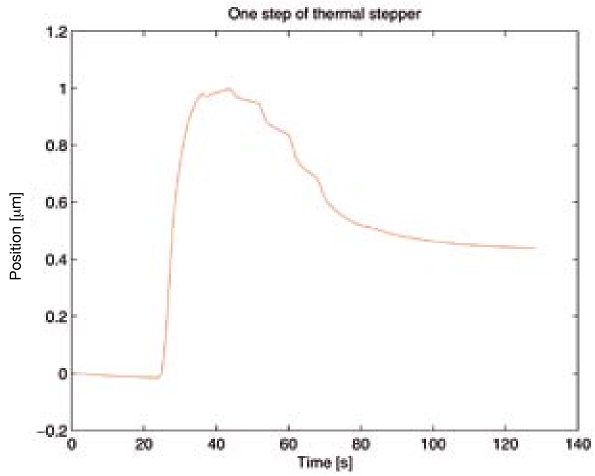
Heating and cooling of the elements is a first-order exponential process that will not reach its final temperature instantaneously. A heating cycle and therefore the movement of the system is not very fast. The alignment itself can be fully automatic, making it possible to align multiple sensors at the same time without human intervention. This reduces hands-on hours and the resulting costs.
Besides for alignment, the mechanism can also be used for on-site sensor calibration. By applying a defined temperature step to all elements simultaneously, it is possible to generate a defined movement of the electrode. This known step can be used for on-site calibration of the sensor and electronics.

Experimental results

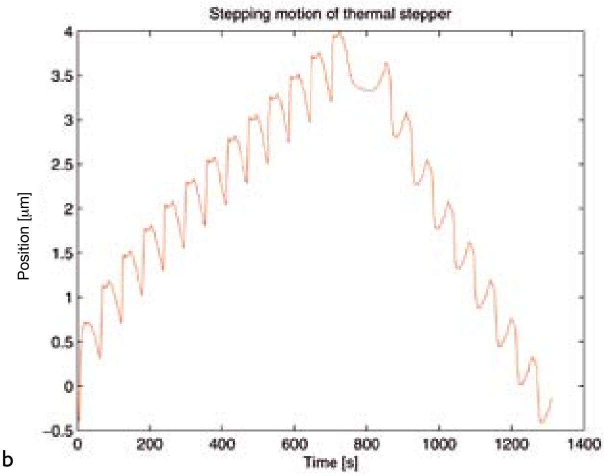
Several test setups have been built to test different aspects of the thermally actuated alignment concept. The performance of the sensor head with auto-alignment can be separated into two different parts by separating the two functions. First the system has to position the two electrodes at the specified distance with limited tilt angle. The second function is to hold them into that position and provide a stable measurement.
The experiments were performed on a system with twelve clamping elements, divided in six groups of two opposing elements. Figure 6a shows the typical movement profile. It can be divided in two parts. First part is the heating of all elements together, which results in the initial upward motion. After this initial heating, the six groups are cooled one after the other. This causes a slight retraction of the electrode. After all elements have cooled down, a permanent displacement has been created. We call this thermal cycle one step. Multiple steps can be made to generate larger movements, both up and down, as depicted in Figure 6b.

Varying step size between a few tens of nanometers and a few micrometers can be obtained by changing heating power. This enables positioning of the sensor electrodes with sub-micrometer accuracy, which is enough to guarantee proper operation of the capacitive sensor.

The second function of the alignment system, providing a stable mount for the electrode during measurement, was evaluated by performing long-term stability measurements. A second electrode was placed on top of the sensor head. The distance between the moving electrode and this fixed one was measured by connecting them to a capacitive read-



a



b

Figure 6: Typical displacement profiles of the thermal stepper for:
(a) one step;
(b) multiple steps.

out circuit, which was especially designed and built for high-stability measurements.
The effect of temperature variations on the setup was kept as small as possible by fabricating as much components as possible from the same material, which enables compensation for thermal expansion of different parts.

The graph in Figure 7 shows the position of the electrode during a 4 hours stability measurement. Position changes due to temperature variations in the lab were removed by compensation with the measured thermal sensitivity (~50 nm/K) of the measurement setup. The resulting signal is smooth and proves that the system is capable of reaching sub-nanometer stability in a controlled environment.

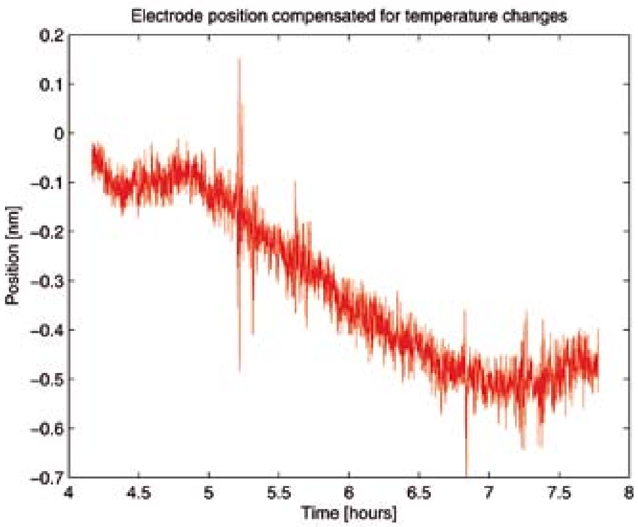


Figure 7. Measured electrode position during 4 hours. The position has been compensated for drift due to the temperature variations.

Realised system

Successful experimental results have resulted in the design and realisation of a functional prototype of the self-aligning sensor head. The prototype is shown in Figure 8**.** It consists of a thermal actuator structure with now sixteen clamping elements, mounted in a rectangular aluminum block. The clamping structure was fabricated by first making the cylindrical shape on the turning lathe. CNC milling was used to cut away the material in between the clamping elements.
As the electrode should be electrically isolated from the clamping structure, it was made as an aluminum conducting coating on a ceramic substrate (aluminum oxide). A small difference in diameter between the electrode and clamping structure of 0.1 mm generates a pretension of around half a Newton per element, which ensures a stable clamping.

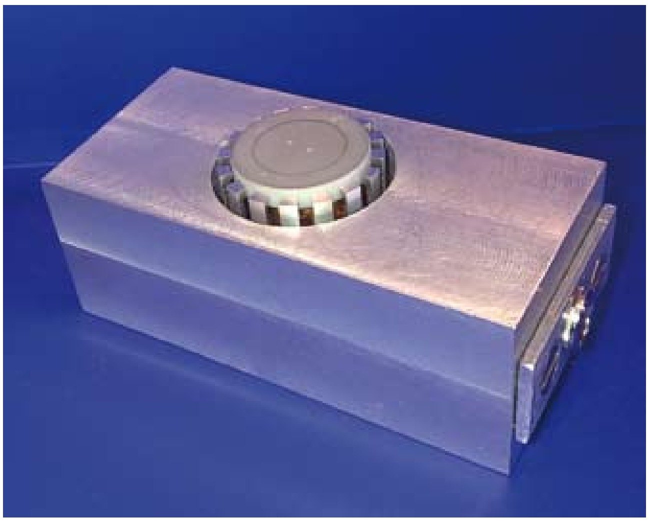


Figure 8. Realised functional prototype of the self-aligning capacitive sensor head. The electrode outer diameter is 22 mm.

Figure 9. The complete electronic control system on a flexible PCB can be mounted inside the clamping structure.

The specific heating sequence of all clamping elements is controlled by an electronic circuit which is integrated in the sensor head. This heating system consists of a flexible printed circuit board with a microcontroller that controls the current through sixteen resistors; see Figure 9. The flex PCB is glued inside the clamping structure, in such a way that the resistors are in contact with the clamping elements and can be used to heat the elements.

Step size and therefore speed of the system is dependent on heating power. The system shown here is able to make steps of ~1 μm at 5 V with a peak current of ~500 mA. A system like this can for example be powered via the USB port of the controlling laptop or PC. This makes the system also useful as stand-alone alignment device, not only for sensor electrodes but also for optical components.

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