Embedded Capacitive Displacement Sensor for Nanopositioning Applications

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Abstract

The scale of nano objects requires very precise position determination. The state-of-the-art manipulators involve accurate nanometer positioning. This paper presents the design of a capacitive displacement sensor for a nanopositioning application. The challenges of designing a capacitor sensitive to nanometer movements that fits in the area of a few hundred square micrometers are described. Analysis of several different designs was carried out using commercial simulation software. Results suggest a sensing resolution of 10 nm displacement. A sensor prototype was fabricated and tested.

Introduction

Nanopositioners equipped with nanoprobes [1] are devices that can precisely manipulate nano-scale objects. The sizes of the nanopositioners used for this work are a few hundreds of micrometers. Motion range is 25 µm to 30 µm and desired step measurement resolution is 1 nm [1]. The 1 nm resolution opens the possibility to control nano-objects: for example nano wires, biological or chemical building blocks. These requirements constrain motion control law specifications in terms of the system precision and dynamic performance. Current motion control accuracy is 8 nm with the use of an embedded optical sensor and the control rate is 500 steps per second.

A critical component in controlling a nanopositioner motion is a displacement sensor. This paper presents initial design of a capacitance based displacement sensor fully embedded within the nanopositioning system. The challenge in this project is to construct an alternative method to an existing optical based displacement sensor and to compare their performance. Various capacitor electrode patterns were explored and their sensitivity due to movement of a nanopositioning platform was evaluated using simulation software. Initial research suggests possible resolution of 10 nm. Simulation results were used for the design and fabrication of an experimental prototype of this sensor.

The Nanopositioner

The Manufacturing Engineering Laboratory of the National Institute of Standards and Technology (NIST), Intelligent Systems Division is developing unique high precision control and positioning robotic systems for nanoscale measurements, manipulation, and standards [1]. A planar one degree of freedom (1-D) nanopositioner constructed at NIST is shown in Fig. 1. It consists of a thermal actuator and a unique platform that is very precisely controlled using an analog Proportional Integral (PI) controller and an optical displacement sensor. At present the capabilities of this device include manipulating a bead with 8 nm precision. The goal is to be able to control the platform with 1 nm accuracy and achieve one thousand cycles dynamic range.

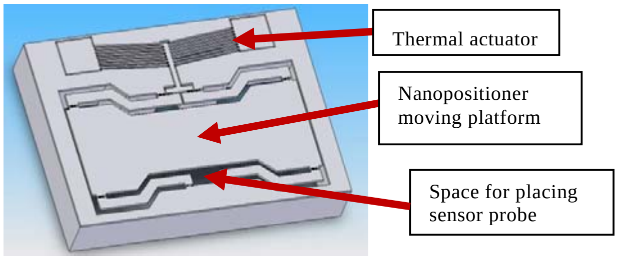


Figure 1. 1-D NIST nanopositioner.

Capacitance Based Displacement Sensor

Most common displacement sensors based on capacitance changes involve parallel plate construction where one of the plates is movable [2]. Since the capacitance is inversely proportional to the distance between the plates the change in capacitance directly relates to the distance measurement with appropriate calibration to account for nonlinearity effects. This idea requires conductive surfaces facing each other and the need to apply the potential difference to both stationary and moving parts. In the case of the NIST nanopositioner it is difficult to fabricate this type of sensor, since it would require depositing metal electrodes on surfaces hidden deep inside the mechanism's trenches. An alternative design would be to create interdigitated capacitor surfaces, but that is difficult considering the wide range of motion and the small air gap requirement of this type of sensor.

Here we are examining the design of a capacitive sensor using open plates [3]. In this case the target object is the movable nanopositioner platform and the sensor probe is placed on the NIST nanopositioner stationary supporting frame surface as indicated in Fig 1.

Initially many different electrode patterns were considered but the comb pattern showed the best sensitivity. Table I shows three different electrode combinations and Figure 2 shows their computer simulation sensitivities.

Table I. Electrode combinations for a sensor with comb pattern. W=width, L=length, T= thickness and S =spacing.

Electrodes					Total capacitance [pF]	Average sensitivity to 10 nm displacement [aF]
No.	W [µm]	L [µm]	T [µm]	S [µm]		
1	2	100	1	2	0.04	3.1
2	10	100	1	1	0.49	2.4
3	5	100	1	2	0.02	2.7

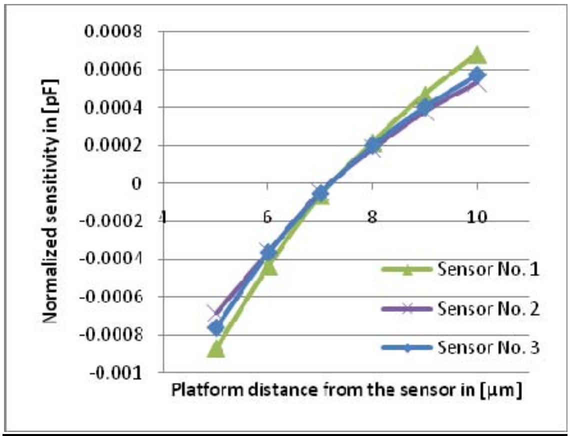
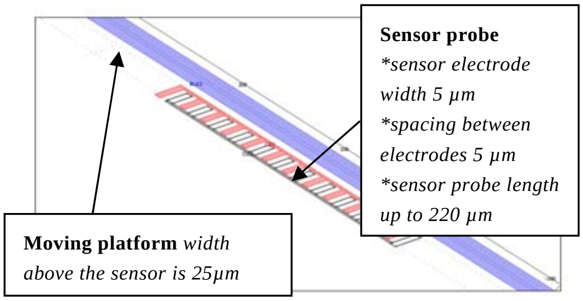


Figure 2. Sensor simulated sensitivity for various electrode arrangements. See Table I for details. Sensitivity is normalized to the average capacitance value in the range from 5 µm to 10 µm.

Sensor Application

The displacement sensor is placed 5 µm away from the home position of the movable platform. Maximum distance between the platform and the sensor is 20 µm. The state-of-the-art in measuring 1 pF capacitance when using commercially available bridge instrumentation has resolution 0.1 aF and the measurement uncertainty is 5 parts in 10^6 at 4.2 kHz rate [4]. This result suggests that reliable capacitance measurements could be provided to the NIST nanopositioner system if the sensor probe is designed to conform to the optimal measurement range of the bridge. The goal is to have about 5 aF capacitance change equivalent to 10 nm displacement. This requirement assumes good signal-to-noise ratio, very low sensor probe dissipation factor, laboratory environment with minimized environmental influences and well defined calibration curve considering the fact that the capacitance-distance relationship is nonlinear.

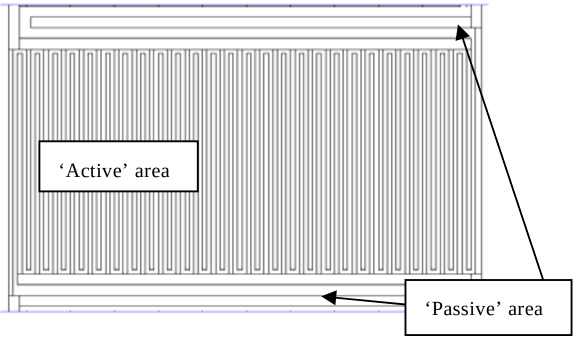
Figure 3 shows the sensor probe concept with several comb electrodes. The sensor length is limited to 220 µm, which is the size of the opening shown in Fig. 1. The width of the sensor probe can be up to 800 µm. These dimensions define the 'active' sensing area. Besides the space considerations, nanofabrication also presents another level of challenges. The most significant constraint is the width of the metal trace and spacing between the electrodes. In particular the issues are how close the electrodes could be made and how well the distance between the electrodes could be maintained.


Sensor probe
**sensor electrode width 5 µm*
**spacing between electrodes 5 µm*
**sensor probe length up to 220 µm*

Moving platform *width above the sensor is 25µm*

Figure 3. Sensor probe concept.

Due to manufacturing restrictions the sensor probe was constructed to have three segments. Directly under the platform there is an 'active' sensor area where the electrodes are most sensitive to platform motion. But this area is very small and total capacitance does not add up to 1 pF which is the optimal capacitance range for using a commercial state-of-the-art capacitance bridge. Two 'passive' sensor areas are added above and below the 'active' sensing area. These segments just offset the capacitance values. They are far away from the platform and are not sensitive to its motion. (See Fig. 4.)


'Active' area

'Passive' area

Figure 4. Displacement sensor. Segment shown has comb planar pattern with 27 electrodes in the 'active' sensing area. Electrode thickness is 1 µm, width is 2 µm and length is 103 µm. The spacing between the electrodes is 2 µm. The nanopositioning platform (see Figure 5) is set above the center of the 'active' area. The 'Passive' sensing area has 19 electrodes above and 19 electrodes below the 'active' sensing area. Each electrode is 211 µm long, 5 µm wide with 5 µm spacing between the electrodes (only 2 'passive' electrodes are shown in Figure 4). The fabricated sensor has a grounded back plate 1 µm thick with a 1 µm SiO_2 isolation layer.

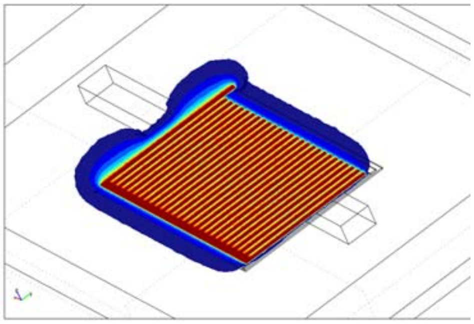


Figure 5. Displacement sensor simulation of electric potential isosurfaces. Only the 'active' sensing area was simulated. The 'Passive' sensing area is not sensitive to platform motion.

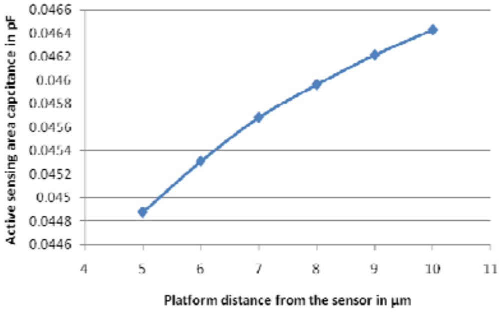


Figure 6. Simulation results for the capacitance sensor.

Table II. Displacement sensor sensitivity to platform motion. Simulation results are given for 10 nm displacement for the various paltform distances from the sensor.

Platform distance interval	Estimated Capacitance difference in aF for a 10 nm platform dispalcement
5 µm to 6 µm	4.3
6 µm to 7 µm	3.7
7 µm to 8 µm	2.8
8 µm to 9 µm	2.5
9 µm to 10 µm	2.1

Conclusions

It is clear from simulation results that the displacement sensor has the potential to detect very small displacements at close range. This protopyte will be used to investigate the issues associated with using a capacitance based sensor in a nanopositiong application. The authors will present the initial measurements using sensor prototypes and compare results with simulations at the CPEM 2010 Conference.

References

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