Three-axis micro-force sensor with sub-micro-Newton measurement uncertainty and tunable force range

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Abstract
The first three-axis micro-force sensor with adjustable force range from \(\pm 20\ \mu N\) to \(\pm 200\ \mu N\) and sub-micro-Newton measurement uncertainty is presented. The sensor design, the readout electronics, the sensor characterization and an uncertainty analysis for the force predictions are described. A novel microfabrication process based on a double silicon-on-insulator (SOI) substrate has been developed enabling a major reduction in the fabrication complexity of multi-axis sensors and actuators.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Miniature force sensors capable of measuring forces in the micro- to nano-Newton range have become a common tool in a variety of fields, such as mechanobiology, material science, microrobotics and life science. In [1, 2] the design of a single-axis capacitive force sensor and its application to study insect flight control, the mechanical characteristics of mouse embryo cells and the threshold for touch sensation in C. elegans [3] are shown. In [4] a sensor based on an optical, diffractive micrograting demonstrates the measurement of the injection forces into drosophila embryos and in [5] the use of an atomic force microscope (AFM), based on optical beam deflection, shows the measurement of molecular interaction forces. A sensor based on the trapping of a magnetic particle in a magnetic field is shown in [6] and is used to measure the force-extension curves of DNA molecules. More recently many of these principles have been employed to develop multi-axis sensors. For many applications additional force components offer a great advantage, e.g. in the case of automated cell injection [7] since a misalignment of the cell and the injection pipette can be detected and compensated. In [8, 9] two three-axis force sensors based on piezoresistive materials are presented and used for the manipulation of embryo cells. A three-axis capacitive force/torque sensor for the measurement of forces and torque acting on a magnetic microrobot has been developed in [10], and in [11] a six-axis force/torque sensor is described.

All these sensors are designed for a specific force range and must be redesigned when used in different applications. It is desirable to have a sensor with an adjustable range to ensure its optimal characteristics for a large variety of applications. Additionally, to date little work has been published on the calibration of multi-axis micro-force sensors and their uncertainty analysis. The results obtained from a sensor are complete only when accompanied by a statement of uncertainty indicating their quality. This paper presents the design, optimization, fabrication and characterization of the first microfabricated three-axis force sensor with sub-micro-Newton measurement uncertainty. The force range of the sensor can be electronically tuned while taking measurements. All the sensors are designed for a specific force range and must be redesigned when used in different applications. It is desirable to have a sensor with an adjustable range to ensure its optimal characteristics for a large variety of applications. Additionally, to date little work has been published on the calibration of multi-axis micro-force sensors and their uncertainty analysis. The results obtained from a sensor are complete only when accompanied by a statement of uncertainty indicating their quality. This paper presents the design, optimization, fabrication and characterization of the first microfabricated three-axis force sensor with sub-micro-Newton measurement uncertainty. The force range of the sensor can be electronically tuned while taking measurements. The sensor calibration and the most important sensor characteristics and their influence on the measurement uncertainty are presented. Finally, the novel microfabrication process is described enabling a major reduction in the fabrication complexity of multi-axis sensors and actuators.

2. Working principle

This work focuses on capacitive force sensing because of its low sensitivity to changes in environmental conditions such
Figure 1. The MEMS-based capacitive three-axis tunable micro-force sensor. The sensor dimensions without the sensor probe are 5 mm by 6 mm and the probe length is 3 mm.

Figure 2. Cross-section of the sensing capacitor visualizing the out-of-plane sensing principle.

Figure 3. Sensor schematic (non-movable, outer frame not shown).

Figure 4. Mechanical response of the sensor to each force component. A force applied in $x$ will result in a parallel movement of the sensing bodies and, therefore, produces only a change in the $x$-capacitance. Since always relatively thick silicon handle layer (H) forms the outer frame of the sensor, whereas the two thin silicon device layers (D) form the active element and the movable body. All the layers are electrically isolated by a silicon dioxide (SiO$_2$) layer. A single device layer would be sufficient to measure displacements in three directions, but the additional layer enables the distinction between positive and negative forces. In this case the differential capacitance $C_1–C_2$ is negative when the inner sensing body moves up ($z > 0$) and positive when it moves down ($z < 0$).

In figure 3, the schematic of the sensor is shown. Due to the unequal sensitivity of transversal in-plane sensing compared to lateral out-of-plane sensing, these degrees of freedom are divided into two sensing bodies suspended within each other. The outer body measures displacements in $x$ and $y$ (and, therefore, forces relative to them) and the inner sensing body displacements (forces) relative to the outer sensing body in $z$.

3. Sensor design

The sensor is designed to measure forces of up to 200 μN in $x$, $y$ and $z$. Multiple sensor configurations (position and geometry of flexures, capacitors and movable bodies) have been analytically compared. Besides the sensitivity criterion for each axis, the most important factor in the multi-axis sensor design is the decomposability of the force components. To ensure a minimum cross-coupling between the different axes, each capacitor pair is dedicated to a single force component and placed such that the main contribution to an output signal can be directly related to the force in the corresponding direction. Therefore, the $x$-capacitor is mainly sensitive to forces in $x$, the $y$-capacitor to forces in $y$ and the $z$-capacitor to forces in $z$. Similar considerations have been made for the flexures, such that by changing the dimensions of the flexures the mechanical stiffness of the sensor can be independently adjusted for each axis.

Figure 4 shows the mechanical response of the sensor to each force component. A force applied in $x$ will result in a parallel movement of the sensing bodies and, therefore, produces only a change in the $x$-capacitance. Since always...
one of the parallel plate capacitor electrodes is longer than the other, a parallel relative movement (as the case for the y-capacitor) will not result in a change of the overlapping area and thus not affect there capacitance, as shown in figure 4(a).

Forces in y result in a rotation of the sensing bodies. To ensure high sensitivity to these rotations, the y-capacitor pair is placed as far from the point of rotation as possible, as shown in figure 4(b). The absolute capacitances in the x-capacitors will both change with the same sign due to a force in y, resulting in no change in the differential capacitance.

Due to the lower sensitivity of lateral sensing, forces in z need to produce a much larger deflection of the capacitor electrodes than forces in x or y. Therefore, an amplification lever is integrated, as shown in figure 4(c), and the z-capacitor is placed as far from the sensor tip as possible to maximize its leverage effect. Using this method, the z-flexure stiffness does not need to be significantly reduced. Additionally, forces in z will only result in a signal in the z-capacitors for two reasons. Firstly, the relative motion of the outer sensing body to the base will equally affect the two capacitors in a pair and, therefore, not change the differential capacitance. Secondly, due to the aspect ratio of the flexures in x and y (much thicker than wide), the out-of-plane motion can be neglected.

An ANSYS finite element model (FEM) has been created to calculate the quantitative mechanical response of the sensor to an applied force at its probe. This enables the optimization of the flexure geometry for a certain target sensitivity along the three axes. The deflections at the position of each capacitor and the corresponding differential signal change were used as the design criteria and the flexure dimensions as the design parameter. Starting with an initial estimate of the flexure dimensions the FEM model was used in an optimization loop to determine the difference from the target deformations in each capacitor and for each force direction. By scaling the flexure dimensions with these errors, the ideal flexure geometry could be found, not only ensuring the desired signal change at the target force in the corresponding capacitor pair, but also minimizing the signals in all the other capacitor pairs. The resulting flexures are shown in figure 5 and their dimensions in table 1. Since all the capacitors need to have electrical contact to the outer frame, two flexures (A and B) at each point had to be fabricated instead of one to produce the required electrical connections.

4. Fabrication


In this work a three-mask process has been developed, similar in complexity to the SOI process published in [10], but enabling three-axis sensors or actuators. It is based on a double SOI substrate with sequential etching of the two device layers by dry etching. Wafer bonding is not required. Even though commercially available double SOI substrates are more expensive, the reduction of photomasks and fabrication steps results in a higher yield rate and, therefore, in a more economical fabrication. In figure 6 the fabrication process is depicted. The photoresist layers are shown only in the steps
involved in the sequential etching of the two device layers (d)–(f).

5. Readout electronics

The electronic readout of the sensing capacitance is based on the impedance relation measurement where two periodic, 180° phase-shifted excitation voltages are applied to a capacitor pair. The demodulated response of the common electrode is then proportional to the ratio of the two capacities [10]. A commercial capacitance-to-voltage converter IC (CVC 1.1, GEMAC) is used to interface each capacitor pair (C1 and C2) on the sensor. This mixed signal-integrated circuit consists of a charge integrator with integration capacitance $C_{\text{int}}$, a sample hold cell, a second-order low-pass filter where the cut-off frequency has been set to 5 kHz and an amplifier stage with an additional gain that can be set by a serial interface. The analog part of the block diagram of the readout is shown in figure 7. Since the sensor is designed to measure positive and negative forces, all the internal operational amplifiers and the output voltage are trimmed to the midpoint of their range of 0–4 V, so forces will result in maximum voltage changes of ±2 V. All the settings are stored in an integrated EEPROM cell. The serial interface and the analog voltage readout have been realized using Labview and a data acquisition card (NI PCI-6259). By changing the values of $C_{\text{int}}$ and gain, shown in (1), the sensitivity of the sensor can be electronically tuned to the appropriate force range of the specific application:

$$V_{\text{out}} \propto \text{Gain} \cdot \frac{C_1 - C_2}{C_{\text{int}}}. \quad (1)$$
6. Sensor characterization

6.1. Calibration

The most commonly used micro-force sensor, the AFM, has led to the development of a large number of methods to

540, Femtotools) is used as a reference, and the uncertainty

as a comparison of the sensor with another standard, a

force sensor system in the micro- and nano-Newton range

multi-axis force sensors and the calculation of their accuracy,

There are some methods published for the calibration of multi-

led to the development of a large number of methods to

However, the accuracy of these methods is unknown since none of them are traceable to the Système International (SI) d’unités. The unit force is derived from the definition of Newton using a combination of base SI units (kg, m and s) [14].

Increasing effort is being made in multiple national

measurement institutes (NMI) to create an SI traceable

reference standard for the calibration of small forces. An

However, when calibrating samples pre-calibrated by another

NMI, even NMI’s show differences of up to 30% in the results [15]. Currently there is no commercial, SI traceable reference force sensor system in the micro- and nano-Newton range available. Therefore, in this work, no claim is made of absolute accuracy in the calibration performed. For the calibration, as a comparison of the sensor with another standard, a commercially available, calibrated micro-force sensor (FTSS40, Femtotoools) is used as a reference, and the uncertainty analysis is carried out relative to this.

There are no standards or norms for the calibration of multi-axis force sensors and the calculation of their accuracy, as they exist in the single-axis case (DIN EN ISO 376) [16]. There are some methods published for the calibration of multi-axis force sensors, e.g. using the shape from motion technique [17], but they are based on mathematical models and, therefore, their accuracy cannot be determined. In this work the sensor is calibrated by subsequently applying a reference force in all directions (x, y and z) using a reference force sensor:

\[
F = V \cdot A.
\] (2)

The goal is to obtain the calibration matrix \(A^{3 \times 3}\), which describes the relationship between the output voltages \(V = [V_x, V_y, V_z]\) of the sensor and the applied forces \(F = [F_x, F_y, F_z]\):

\[
V_c = \begin{bmatrix}
V_{x1} & \cdots & V_{x4} \\
V_{y1} & \cdots & V_{y4} \\
V_{z1} & \cdots & V_{z4}
\end{bmatrix}
\] (3)

\[
F_c = \begin{bmatrix}
F_{x1} & \cdots & 0 & \cdots & 0 & \cdots & 0 \\
0 & \cdots & F_{y1} & \cdots & F_{y4} & \cdots & 0 \\
0 & \cdots & 0 & \cdots & F_{z1} & \cdots & F_{z4}
\end{bmatrix}
\] (4)

As mentioned in section 3, the mechanical stiffness is different in each axis. Therefore, the number of calibration data points will be different in each direction. Before solving the system of equations, the raw calibration force and voltage data (3, 4) are linearly interpolated \(F_{c,ipol}, V_{c,ipol}\) thereby weighting each axis equally. Using the least-squares method (6) and minimizing the residual \(r\), the best estimate of the calibration matrix \(\hat{A}\) is found. To facilitate the understanding of the uncertainty analysis, shown in the next section, the system of equations is divided into three systems. (The results of the calibration are shown in section 6.3.)

\[
F_{c,ipol} = V_{c,ipol} \cdot \hat{A} + r_{\text{min}}
\] (5)

\[
\hat{A}_j = \left(V_{c,ipol}^T \cdot V_{c,ipol}\right)^{-1} \cdot V_{c,ipol}^T \cdot F_{c,ipol}
\]

with \(j = x,y,z\)

\[
\hat{A} = [\hat{A}_x, \hat{A}_y, \hat{A}_z],
\] (7)

6.2. Sensor characteristics and measurement uncertainties

The result of a measurement is only an approximation of the value of the measurand and, thus, is complete only when accompanied by a statement of the uncertainty of that estimate [18]. The measurement uncertainty is a parameter associated with the results of a measurement that characterizes the dispersions of the values that could reasonably be attributed to the measurand [19]. Therefore, besides the calibration matrix and the corresponding sensing range, the most important characteristics of the sensor are measured and their influence on the measurement uncertainty calculated.

- **Force range.** The maximum measurable force can be found by multiplying the calibration matrix with the maximum voltage change in all axes (±2 V).

- **Resolution.** The smallest force increment that can be detected, limited by the noise in the sensor output. The uncertainty in the force measurement due to noise is given by the standard deviation of the output voltages multiplied by the calibration matrix.

- **Sensor drift.** The change in the output signal without any change of the applied force over a certain time period. The uncertainty due to drift is calculated using (8), the root mean square of the voltage change \(\Delta V\) in the time period \(t\) (10 s), where \(n\) is the number of intervals measured over:

\[
\delta_j(t) = \sqrt{\frac{\sum_j \Delta V_j(t)^2}{n-1}} \cdot \hat{A}_j.
\] (8)

- **Cross sensitivity.** Sensitivity of a sensor output to a force applied in another direction. This characteristic is related to how good the sensor can separate the different force components from each other.

- **Nonlinearity.** The calibration matrix is a linear representation of the sensor. A nonlinearity in the sensor’s characteristics can result in a measurement error and, therefore, to an increased uncertainty in the results.

- **Uncertainties in the calibration matrix.** All sources of uncertainties related to the calibration matrix, such as the cross-sensitivity and nonlinearity, are combined. The uncertainty in a force prediction shown in (9) can be calculated using the covariance matrix in (10) and the mean square error \(\delta_j^2\) in (11), where \(n + h + k\) is the number of calibration data points. For these calculations the raw calibration data \(V_{c,ipol}, F_{c,ipol}\) are used. The diagonal elements in each of the covariance matrices are the variances of the components in the calibration matrix:
6.3. Sensor tuning and the corresponding characteristics

Depending on the application, a specific force range is required. By tuning the range of the sensor, the ideal sensor characteristics and the smallest possible measurement uncertainties can be guaranteed. Therefore, the sensor is characterized for a number of different settings of the readout electronics. The integrator capacitance $C_{\text{int}}$ has been varied from 1.2 pF to 6.0 pF in 0.2 pF steps and the amplifier gain from 2.2 to 4.0 in 0.2 steps. For each combination of these two parameters the sensor has been calibrated five times along each axis, the sensor characteristics have been recorded and the corresponding measurement uncertainties calculated. The resulting data sets for $x$, from a total of 3750 calibrations, can be seen in figure 8. The raw characterization data are shown as +, whereas the surface plots show a fit using a second-order polynomial in two variables, fitted using a least-squares algorithm.

Using this setting range the force range of the sensor can be changed from approximately ±20 μN to ±200 μN. The calibration curves for the minimum and maximum sensor range are shown in figure 9. The arrows between the main components, which correlate with the diagonal elements in the calibration matrix, indicate the range in which the calibration curves can be adjusted. The corresponding uncertainty components are shown in table 2. The non-diagonal entries in the calibration matrix are approximately zero, which can be verified in the calibration plots. This is an indication that the goal, to mechanically decompose the forces, has been successfully realized. Depending on the application and

\[
\mu_{\text{Prediction},j} = \sqrt{\delta^2_j + \text{Var}(\hat{A}_j) \cdot V_p^T} \tag{9}
\]

\[
\text{Var}(\hat{A}_j) = \delta^2_j \cdot (V_c^T V_c)^{-1} \tag{10}
\]

\[
\delta^2_j = \frac{(\hat{F}_j - F_j)^T (\hat{F}_j - F_j)}{n + h + k - 3} \quad \text{with} \quad \hat{F}_j = V_c \cdot \hat{A}_j. \tag{11}
\]

- **Expanded combined uncertainty.** By combining all the sources of measurement uncertainty together and multiplying them with the coverage factor $k$, the expanded combined uncertainty can be calculated as shown in (12).

\[
u_j = k \cdot \sqrt{\mu_{j,\text{Drift}}^2 + \mu_{j,\text{Noise}}^2 + \mu_{j,\text{Prediction}}^2}. \tag{12}
\]

- **Resonate frequency.** The bandwidth of the sensor is limited by the lowest resonant frequency of 1570 Hz, measured using a laser Doppler vibrometer and validated using FEM modeling.
Table 2. Sensor characteristics at two different electronic settings.

<table>
<thead>
<tr>
<th>Gain</th>
<th>4</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_v$ (pF)</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td>$A$ ($\mu N V^{-1}$)</td>
<td>$\begin{bmatrix} 10.80 &amp; 0.39 &amp; 2.12 \ 0.24 &amp; 9.89 &amp; 0.80 \ -0.04 &amp; -0.24 &amp; 18.44 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 95.61 &amp; -0.42 &amp; -0.20 \ -1.11 &amp; 83.43 &amp; -3.50 \ -2.12 &amp; -0.02 &amp; 109.18 \end{bmatrix}$</td>
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Sensing range ($\mu N$)
- $F_x$: ±22 ±192
- $F_y$: ±20 ±176
- $F_z$: ±31 ±222

Mechanical resonant frequency (lowest) 1570 Hz

Uncertainty: noise measured at 10 Hz readout frequency ($\mu N$)
- $x$: 0.03 0.11
- $y$: 0.03 0.07
- $z$: 0.05 0.12

Uncertainty: drift over 10 s ($\mu N$)
- $x$: 0.01 0.04
- $y$: 0.01 0.04
- $z$: 0.02 0.07

Uncertainty: prediction ($\mu N$)
- $x$: 0.17–0.20 4.46–4.51
- $y$: 0.23–0.26 4.69–4.75
- $z$: 0.09–0.10 2.54–2.57

Figure 9. The calibration plots of the force sensor for two different readout settings. Squares indicate the raw calibration data $V_x$, circles $V_y$ and triangles $V_z$.

The main contribution in the uncertainty components, shown in table 2, comes from the uncertainty in the force prediction. The upper level in these intervals corresponds to the uncertainty at the maximum output voltage of the sensor and the lower limit to the minimum which is proportional to the root mean square of the difference between the calibration data and the force prediction. Therefore, fluctuations and nonlinearities in the calibration curves, as seen in figure 9, have a major influence in the calculation of the measurement uncertainty. These fluctuations are artifacts of the calibration method and demonstrate the major challenge of applying reference force vectors at exact locations and orientations without damaging the fragile sensor structures.

7. Conclusion

An electronically tunable three-axis micro-force sensor, its design, fabrication and characterization have been presented. It has been designed such that the cross-sensitivities and additional uncertainties related to cross-sensitivity are reduced. The designed sensor enables force measurements in a range between ±20 $\mu N$ and ±200 $\mu N$ with a resolution down to 30 nN. Due to the unavailability of a commercial, SI traceable reference force sensor in the micro- and nano-Newton range, the measurement uncertainties have been evaluated relative to a reference force sensor in the 0.1 $\mu N$ range at the highest resolution. The main contributions of this work are as follows.

- The first three-axis micro-force sensor enabling force measurements of sub-micro-Newton.
- A tunable force range, enabling the sensor to be optimized for an application while measuring.
• A novel three-mask fabrication process enabling the fabrication of three-axis transducers with a major reduction in fabrication complexity.

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