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# 6 DOF Force and Torque Sensor for Micro-manipulation Applications

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**Abstract**

This paper presents the design, fabrication and characterization of a piezoresistive 6 Degrees of Freedom (DOF) force and torque sensor to be used in micro-manipulation. The mechanical structure of the device consists of 7 suspended beams and a calibration structure, which can be replaced by micro-manipulation tools such as micro-grippers or probes. The geometry of the beams and the location of the piezoresistors in the structure are optimized to reduce crosstalk and improve the sensitivity. A linear regression model is fitted to the calibration data to extract the forces and torques from the resistance variations detected in the piezoresistors. The device has been fabricated with an IC-compatible process and successfully characterized. The data acquisition system is programmable, allowing for dynamic adjustments of the trade-offs between noise levels, accuracy and bandwidth. Depending on the axis, the linear range of the sensor reaches 4 to 30mN in forces and 4 to 50 μN·m in torques. During calibration, root mean square errors up to 17 to 45 μN and 14 to 40 μN·mm were observed in the measured data, respectively.



*Keywords*: 6 DOF force sensing, micro-manipulation, piezoresistive sensor, MEMS

## 1. Introduction

Force and torque sensing are essential in micro-manipulation, both to execute operations reliably and to avoid damaging fragile objects. Force and torque information is used in automatic handling systems, e.g. to prevent that micro-grippers and other micro-tools exert too high forces on the micro-parts. In human tele-manipulation such detected forces can be fed-back to the user through haptic interfaces. Typical fields

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in which the control of the forces and torques are needed include handling and assembly of MEMS and MOEMS [1], and life sciences (cells manipulation) [2]. In these applications components have typical dimensions in the micrometer range (up to a few hundreds of micrometers), and due to their fragility the force and torque to be controlled are respectively in the mN and mN·mm range with µN and µN·mm resolution.

Several force-sensing devices have been developed, but most of them measure the forces in a limited number of degrees of freedom (DOF) [3][4]. Only a few are able to monitor loads along 6 DOF [5][6]. Moreover, most of the developed sensing devices adopt symmetric structures to eliminate crosstalk. This limits the access to probing points and the integration of manipulation tools. The only asymmetrical 6 DOF micro-force sensor known by the authors is the capacitive sensing device developed in [6].

In this paper, an asymmetrical 6 DOF micro-force and torque sensor based on piezoresistors is presented. Thanks to its IC-compatible production process and its asymmetrical structure, the device can be integrated in the fabrication of silicon micro-grippers and micro-probes. The device has the capability of detecting forces and torques in the mN and mN·mm range, with resolution in the µN and µN·mm range, respectively.

## 2. Device Design

The proposed device consists of a silicon structure with implanted piezoresistors to measure the stress induced by the application of loads to the silicon structure. Piezoresistive sensing elements are suitable to detect force and torques with the above mentioned specifications, and are compatible with IC processes for the fabrication of micro-manipulation tools, such as micro-grippers or probes. The final geometry (Figure 1-a) is the result of an optimization process that has considered the dimensions of the structure, and the number, the location, the interconnection of piezoresistors, to achieve a high sensitivity and a low crosstalk, at as high as possible stiffness. The 6 DOF sensor, with a total dimension of 3 x 1.5 x 0.03 $mm^3$, features an asymmetrical geometry composed of 7 suspended beams and a calibration structure. 16 measuring piezoresistors are put in the high stress concentration regions of the beams and 8 reference piezoresistors in the low stress concentration areas of the device. The calibration structure presents micro-fabricated features to apply the calibration forces in precise locations, and can be replaced by micro-manipulation tools during the fabrication process. The device is fabricated with an IC-compatible process [7]. A SEM picture of the device is shown in Figure 1-b.

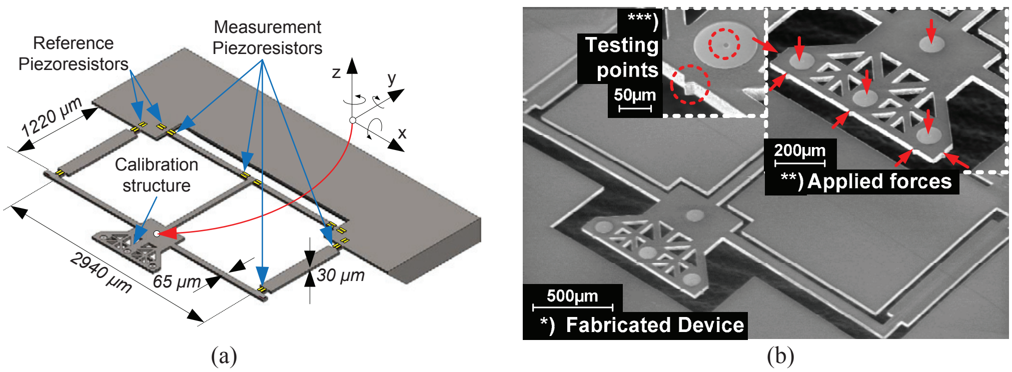


Figure 1: (a) Designed structure for the 6 DOF force and torque sensor. The calibration structure can be replaced by micro-manipulation tools. (b) SEM images of the fabricated sensor (*), the calibration structure with the locations of applied calibration forces (**), and the micro-fabricated features on the calibration structure for force application (***).

## 3. Device calibration and performance

The sensor is characterized with the strategy shown in Figure 2-a. A 1 DOF force probe from Femtotools (supported by a motorized stage) is pushed against the micro-fabricated features of the calibration structure. After applying the force, the piezoresistors are connected, one at a time, to an external Wheatstone Bridge through a National Instruments PXI2536 crosspoint matrix switch. In this way, all resistances are measured with a single amplifier and DAQ channel.

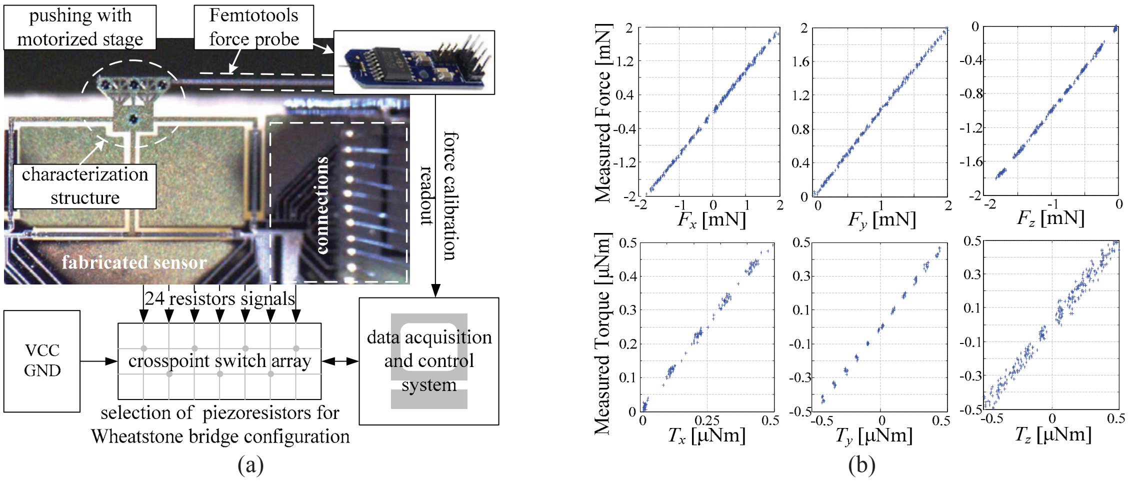


Fig. 2: (a) The sensor is bonded to a PCB and all resistors are connected to a crosspoint switch array. A single readout channel is used to measure all piezoresistors. (b) Measured loads (Force and Torques) versus applied loads in the 6 DOF.

Force ramps are applied several times in nine points of the calibration structure (Figure 1-b). The resistance of all piezoresistors is recorded, together with the applied 6 DOF load. The 6 components of the load are calculated from the 1 DOF force measurement, taking into account the direction of the force and the location of the micro-fabricated features. Using the acquired data, a linear relation is fitted between the variation of the values of the piezoresistors and the applied loads. A calibration matrix $A$ is obtained by a linear least-square fit of Equation 1 to the acquired data, such that the root mean squared error (RMSE) between observed and fitted values is minimized.

$$\frac{\Delta R}{R}_{N_{mpr}\times 1} \times A_{6\times N_{mpr}} = F^{fitted}_{6\times 1}$$
$$N_{mpr} = \text{Number of measurement piezoresistors} \qquad (1)$$
$$N_s = \text{Number of samples}$$

Figure 2-b shows the relation between the reference loads and the result calculated using the $A$ matrix from Equation 1, featuring good correspondence, no crosstalk and a linear behaviour. Care is taken to align the 1 DOF force sensor relative to the calibration structure. Nonetheless, some misalignment is always present which is the main cause for the remaining calibration error. Table 1 shows the RMSE obtained after the calibration of the device, as well as the linear range of the sensor (considering up to 10% of strain), and its stiffness.

Table 1: Measured sensor performance in the 6 DOF.

| DOF | $F_x$ | $F_y$ | $F_z$ | $T_x$ | $T_y$ | $T_z$ |
|---|---|---|---|---|---|---|
| Linear range (mN, mN·mm) | 13 | 30 | 4 | 4 | 7 | 50 |
| Stiffness (N/m, mN·mm/rad) | 1363 | 1695 | 97 | 137 | 306 | 1955 |
| Calibration RMSE (µN, µN·mm) | 45 | 26 | 17 | 14 | 20 | 40 |

## 4. Conclusions

This work has shown that 6 DOF micro-force and torque sensing can be achieved with piezoresistive elements integrated in an asymmetrical micro-structure. The simplicity of the fabrication, the specifications of the device and the asymmetrical geometry makes the device very suitable for sensorized micro-manipulation.

A 6 DOF sensor has been developed and experimentally characterized, achieving a range of 4 to 30 mN in forces and 4 to 50 mN·mm in torques, with calibration RMSE up to 17 to 45 µN and 14 to 40 µN·mm respectively. The calibration and processing of the measured data successfully eliminates any crosstalk between the signals, which could be caused by the asymmetrical geometry of the sensor. Such geometry makes the sensor innovative and versatile because of the simple integration of micro-tools in the same substrate of the sensor: the 6 DOF piezoresistive sensor and micro-tools can be produced in the same fabrication process.

As future developments, real-time measurements will be done to assess the noise levels at different filtering bandwidths. The reconfigurable acquisition system used (programmable switch matrix together with the processing of the data) will allow to test different configurations, or to dynamically adjust trade-offs of accuracy and sampling rates. After the integration of micro-tools in the same substrate is achieved, the full device will become a system of paramount potentiality for sensorized micro-manipulation.

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