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Design of a Small-Scale Tactile Sensor with Three Sensing Points For Using in Robotic Fingertips

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Abstract— **This paper describes our initial research on development of a tactile sensor, which can be employed in anthropomorphic soft fingertips, with multi-sensing points that uses 3-DOF micro force moment sensing chips (MFMS) which are able to measure forces up to nearly a Newton. Three sensing points are integrated on a compact printed circuit board with an in-built multiplexer circuit for the purpose of saving energy and reducing the number of outputs. This system was designed for the purpose of manipulating small-scaled objects, and realizing special characteristics of the objects such as distribution of edges/borders. The process including design, fabrication, and calibration will be explained in detail in this paper.**

I. Introduction

Touch is a common but important action of everyday life. It permits us to approximately determine the surface properties and other properties of an object, including its weight and shape, facilitating grasping tasks, as well as to determine many functions of the motor system. Until the 1970s, however, research about touching was limited to psychophysical studies. Since neural mechanisms underlying tactile sensation have been found to be critical to the success of adept manipulations [1], recent robotics research about dexterous manipulation has sought to imitate the natural touch mechanism, as well as the anatomy, of human fingers to optimize the ideal anthropomorphic artificial hand. Among the factors constituting an artificial hand, tactile perception is the most important. Without tactile feedback, failures in adapting manipulation can occur, both for humans and robots. Nowadays, thanks to the development of MEMS (Micro Electro Mechanic System) technology, tactile systems have been miniaturized, and become multi-functional, highly integrated, and applicable [2]. Beccai *et al*. [3] fabricated a tactile sensing skin using miniaturized silicon-based sensor which can detect three components of external force up to some Newtons. Engel *et al.*[4] developed an integrated flexible tactile sensing skin which is not only sensitive to common surface characteristics such as frictional force, roughness; but also thermal conductivity, hardness, and temperature. Shinoda *et al*[5]. designed a flexible EMG (Electromyography) sensor array without any wiring by employing Two-Dimensional Communication skin to transfer both signal and electric power supply. Off-the-shelf tactile array sensing sheet (Nitta, Japan) with the thickness around 0.1mm, is flexible and able to acquire the information of stress distribution acting on the surface [6]. However, sampling time is quite small, highest at 100 Hz, which is not suitable for dynamic application. Aforementioned researches, however, were found to be complicated in design and fabrication.

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This paper describes design, fabrication, and calibration of small-scale tactile soft-contacting sensor with three sensing points. Each sensing point is a 3-DOF (degree of freedom) MFMS (Micro Force Moment Sensing) chip which can detect force/moment around three axes. This chip, whose size is 2 mm x 2 mm x 0.5mm (length x width x height), works basing on measurements of changes of resistance of piezoresistors diffused on a single Si base. Three chips are placed on a compact circuit board with inbuilt necessary electronic circuits, such as offset cut-off, multiplexer circuits. Ultimately, three small soft tips cover three sensing chips to form a complete soft tactile sensor.

II. Overall Design of Tactile Sensor

A. Idea

To perceive the distributed information at different positions, it is necessary to place many sensing chips at various placements on the sensor. It is natural that, the more sensing points, the more diverse the distributed information is. Nevertheless, the number of sensing points is not necessarily large because this design would cause troubles in wirings and data processing. Also, these sensory points must not be too closed or too far each to the other. After consideration, number of sensory points and the arrangement were decided as illustrated in Fig. 1. Three sensing points are distributed on three peaks of a planar equilateral triangle with the length of each side being 6 mm. Reasons for this design are such that:

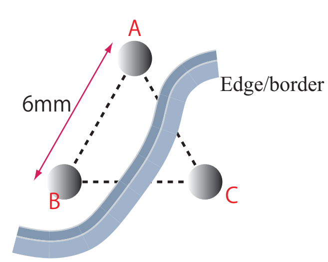

Fig. 1. Arrangement of three sensing points form an equilateral triangle.

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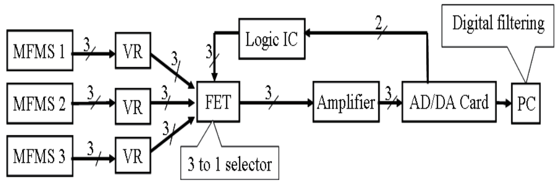


Fig. 2. Overview of the sensing system.

1) Three points creates a plane. Therefore, it is easier to realize surface of an object (flat, convex, curved, etc.) while exploring on it.
2) If one or two sensors generate different information compared with remained one, it is possible to conclude that the fingertip is at the border/edge
3) Putting three sensors on an equilateral triangle assures symmetry of this sensory system.

B. Overall Design

Fig. 2 shows a flowchart of a complete tactile sensing system covering from hardware to soft ware. Three sensory points are three MFMS chips which will be reported in the next section. Also, three offset-cut-off circuits, using variable resistors (VR) to get rid of offset values when three MFMS chips are at free states, are also employed. All signals from three MFMS chips are led to the multiplexer circuit using FETs (Field Effect Transistors); and AND, INVERTER gate chips. By using this design, number of outputs is unchanged compared with case using one MFMS chip. All mentioned modules are integrated on one PCB (Printed Circuit Board). Picking one MFMS chip at specific time is controlled by two logic bits generated by DAC (Digital to Analog Converter) PCI card. Outputs are amplified with definite gain and wired to AD (Analog to Digital Converter) PCI card. Furthermore, a data acquisition software was built using Microsoft Visual C++ to control the multiplexer circuit, collecting data, implementing digital filtering, and displaying results on the monitor. Hereafter are detailed descriptions of each module.

III. Micro Force/Moment Sensing Chip

A. Working Principle

The sensing structure of the MFMS chip is shown in Fig. 3 with piezoresistors diffused at suitable places on the sensing beam. The chip is designed to detect independently the force F_z and moments M_x, M_y applying to the center of chip. The beams are aligned on a plane of single crystalline silicon. The dimensions of each beam are decided to be 800 μm x 100 μm x 75 μm (length x width x thickness), and the chip size is 2 μm x 2 μm x 0.45 μm . The four pedestals at the corners of the beams are fixed, and the forces are applied at the center plate. Piezoresistors are designed on the surface of all beams, which are categorized into two types: ones to detect longitudinal (normal) stresses and the others do shear stresses. The arrangement of piezoresistors on the beams is shown in Fig. 3, and detailed explanation

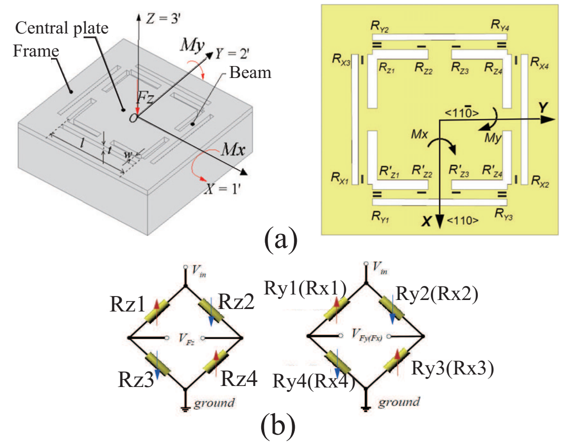


Fig. 3. Design of the sensing chip: (a) Arrangement of piezoresistors on the beams. (b) Wheatstone bridges to measure F_z, M_x, and M_y

can be referred to [7]. All the piezoresistors are suitably connected to form three Wheatstone bridges to measure three components of force and moments as shown in Fig. 3. By integrating the Wheatstone bridges on chip, it requires no external transducer circuits which abate the complications in implementation. When an external force is applied on the chip, it deforms the four beams and changes the resistances of the piezoresistors, which leads to changes in outputs of corresponding measurement circuits. We hereafter explain the detection principle of F_z. M_x, and M_y which have similar principles. When the resistances of piezoresistors $R_{F_{zi}}$ are changed due to stress, the output voltage is expressed by:

$$V_{Fz} = \frac{r}{(1+r)^2}\left(\frac{\Delta R_{F_{z1}} + \Delta R_{F_{z4}}}{R_{F_{z1}} + R_{F_{z4}}} - \frac{\Delta R_{F_{z2}} + \Delta R_{F_{z3}}}{R_{F_{z2}} + R_{F_{z3}}}\right) V_{in} \quad (1)$$

where:

$$r = \frac{R_{F_{z1}} + R_{F_{z4}}}{R_{F_{z2}} + R_{F_{z3}}} \quad (2)$$

Piezoresistors R_{Fzi} $(i = 1,..,4)$ are designed to be identical, thus $r = 1$. When a vertical force F_z is applied to the center of the sensing chip, the longitudinal stresses in all piezoresistors of the F_z bridge can be written as:

$$\sigma_{R_{F_{z1}}} = \sigma_{R_{F_{z4}}} = -\sigma_{R_{F_{z2}}} = -\sigma_{R_{F_{z3}}} \quad (3)$$

where $\sigma_{R_{F_{zi}}}$ is the longitudinal stress at piezoresistors $R_{F_{zi}}$ $(i = 1-4)$. Therefore, the following relationship is satisfied:

$$\Delta R_{F_{z1}} = \Delta R_{F_{z4}} = -\Delta R_{F_{z2}} = -\Delta R_{F_{z3}} \quad (4)$$

Finally, output voltage of the F_z bridge can be shown as:

$$V_{outFz} = \frac{1}{2}\frac{\Delta R_{F_{z1}}}{R_{F_{z1}}} V_{in} \quad (5)$$

Due to the symmetry of the arrangement of piezoresistors and the structure of the sensing chip, resistance change in each arm satisfied $\Delta R_{M_{y1}} = -\Delta R_{M_{y2}} = -\Delta R_{M_{y3}} = \Delta R_{M_{y4}}$, therefore the M_y-bridge is still balanced. It happens similarly in case of M_x-bridge. As a result, crosstalk between each

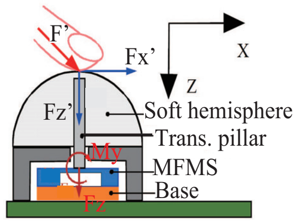


Fig. 4. Force/moment analysis of contacting operation.

bridges is eliminated. Measurement principles are the similar for M_x, and M_y Wheatstone bridges.

To transfer force to the sensing chip, a silicon transmission pillar is inserted into the plate of the MFMS. When touching action is made to the sensor in Fig. 4, the touching force F' can be decomposed into 3 components F'_x, F'_y, and F'_z acting on the soft contact part, and through the transmission pillar, these forces will be transmitted to the MFMS chip, and can be expressed by 3 components F_z, M_x and M_y. The force and moments F_z, M_x and M_y will be detected by MFMS chip. The relationship between the applying forces (F'_x, F'_y, F'_z), and the resultant forces on the chip (F_z, M_x, M_y) can be written as below:

$$\begin{pmatrix} M_y \\ M_x \\ F_z \end{pmatrix} = \begin{pmatrix} l_p\alpha & 0 & 0 \\ 0 & l_p\alpha & 0 \\ 0 & 0 & \beta \end{pmatrix} \begin{pmatrix} F'_x \\ F'_y \\ F'_z \end{pmatrix} \tag{6}$$

where l_p is is the length of the transmission pillar; α and β represent for the damping of the rubber material. On the other hand, the applying forces (F_z, M_x, M_y) on the MFMS chip will generate output voltages as expressed in the equation below:

$$\begin{pmatrix} V_{M_y} \\ V_{M_x} \\ V_{F_z} \end{pmatrix} = \begin{pmatrix} S_{M_y} & 0 & 0 \\ 0 & S_{M_x} & 0 \\ 0 & 0 & S_{F_z} \end{pmatrix} \begin{pmatrix} M_y \\ M_x \\ F_z \end{pmatrix} = S \begin{pmatrix} M_y \\ M_x \\ F_z \end{pmatrix} \tag{7}$$

where S_{M_y}, S_{M_x}, and S_{F_z} are the sensitivities of the MFMS chip to My, Mx, and Fz, respectively.

Finally, from equation (6) and (7), we have:

$$\begin{pmatrix} V_{M_y} \\ V_{M_x} \\ V_{F_z} \end{pmatrix} = S \begin{pmatrix} l_p\alpha & 0 & 0 \\ 0 & l_p\alpha & 0 \\ 0 & 0 & \beta \end{pmatrix} \begin{pmatrix} F'_x \\ F'_y \\ F'_z \end{pmatrix} \tag{8}$$

or:

$$\begin{pmatrix} V_{M_y} \\ V_{M_x} \\ V_{F_z} \end{pmatrix} = \begin{pmatrix} S_{F'_x} & 0 & 0 \\ 0 & S_{F'_y} & 0 \\ 0 & 0 & S_{F'_z} \end{pmatrix} \begin{pmatrix} F'_x \\ F'_y \\ F'_z \end{pmatrix} = S' \begin{pmatrix} F'_x \\ F'_y \\ F'_z \end{pmatrix} \tag{9}$$

Two sensitivity matrices S and S' will be determined by calibration process reported in section VI below.

B. Fabrication

The fabrication process consists of a six-mask process shown in Fig. 5. The starting material is n-type SOI wafer with surface crystallographic orientation. The thicknesses of the device layer, handle layer and buried oxide layer are 75 μm, 375 μm, and 1 μm, respectively.

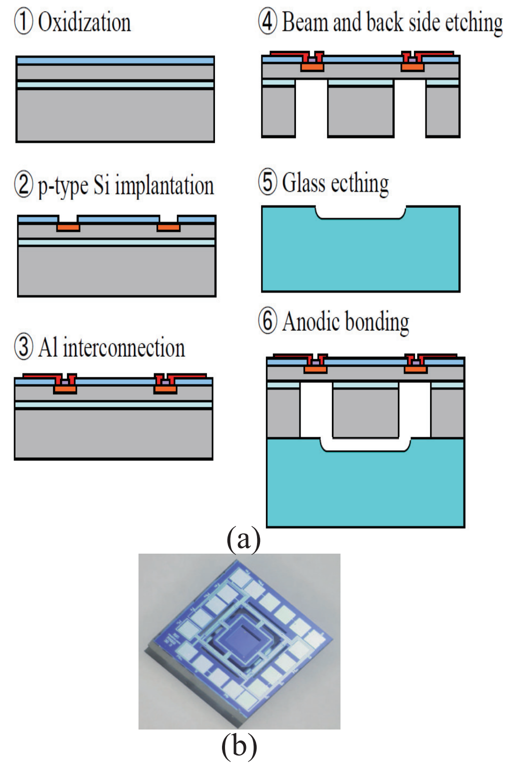


Fig. 5. Fabricated chip: (a) Fabrication flow of the MFMS chip. (b) Micrograph of fabricated 2 mm^2 chip.

Firstly, silicon dioxide layers were grown on both sides of the SOI wafer by the thermal oxidation process. The thickness was grown to be about 0.3 μm. Next, photolithography was conducted on the front side of the wafer to pattern piezoresistors with their principal axes aligned with the crystal orientations ($1\dot{1}0$) and (110). Then p-type Si piezoresistors were created by implantation of boron ion with a dose of 4x10^{15}/cm2 at 50 keV energy, and a subsequent ion activation process was performed at 1100^{o}C in oxygen for 30 minutes. Surface impurity concentration was about 1x 10^{19} cm^{-3}, and the resistance of each piezoresistor was 650 Ω . After contact holes are opened by BHF solution, Al interconnection was created by sputtering, photolithography, and Al etching. Then the deep reactive ion etching process was done on the front and back sides of the wafer to form the beams. Buried oxide was removed by RIE. Finally anodic bonding was performed to fix the chip to the overload protection glass base. The gap of the overload protection base is 5 μm, which is safety distance for the center plate to move. Fig. 5(b) shows a fabricated MFMS chip. A 350 μm x 350 μm x 75 μm square-shaped cavity at the center of the chip is used for locating the transmission pillar.

IV. Electronic Design

As stated above, each sensing point can generate three components of force/moment. Each signal requires two

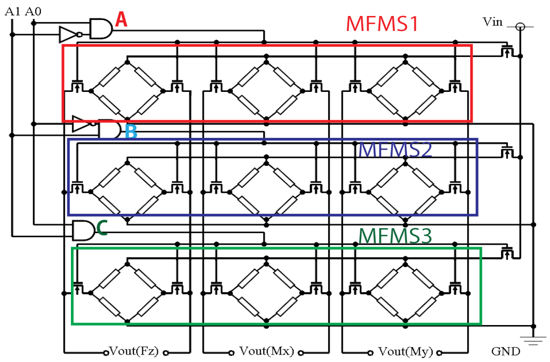
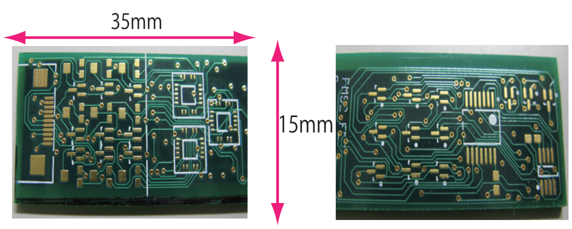


Fig. 6. Scheme of the multiplexer circuit.



(a) Front view (b) Bottom view

Fig. 7. PCB (Printed Circuit Board) of the sensor.

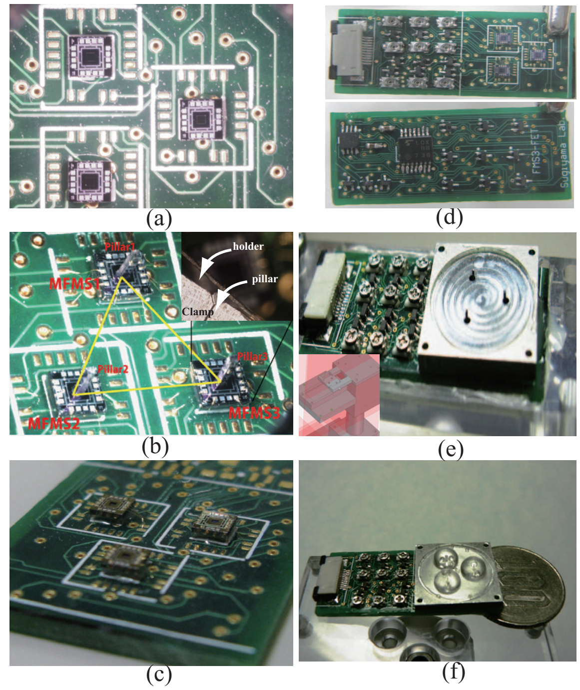


Fig. 8. Packaging process of the tactile sensor.

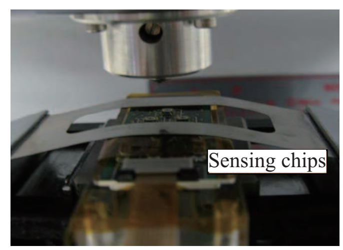


Fig. 9. Setup for calibrating three MFMS chips.

wiring outputs of one Wheatstone bridge, for example F_z^+ and F_z^- . Therefore, there would be eighteen wiring outputs of three MFMS chips which cause complication in fabrication and implementation. For that reason, we designed an inbuilt electronic offset cut-off and, especially, a multiplexer circuit. With this design, the number of outputs of the sensor is reduced into one third, *i.e.* equaling to that of one MFMS chip. Among various type of multiplexer circuit, an FET (Field Effect Transistor)-based multiplexer was selected because of its simplicity and compactness. Fig. 6 shows a principle schematic for the multiplexer circuit and three MFMS chips. FETs are connected to the voltage supplying line, and two outputs of one Wheatstone bridge to assure that states ON or OFF of these FETs can control states of entire the bridge circuit. The multiplexer circuits have to activate three Wheatstone bridges of one MFMS chip at a specific time. Also, because of three sensory points, the multiplexer needs two logic bits to decode selection of each MFMS chip. Two control bits A_0 and A_1 (Fig. 6) are led to AND and INVERTER logic gates to implement decoding. Outputs at points A, B, and C decide operations of three MFMS chips. At one instant, only one output among A, B, and C is activated HIGH ("1" logic), whereas others are LOW ("0" logic). Table 1 shows selected MFMS based on logic values of value A0 and A1. Detailed operation is as followed:

1) A_1=0, A_0=0: outputs at A, B, and C are all LOW causing all the FETs to be on the OFF states. There is no MFMS chip is selected, and no outputs as well.
2) A_1=0, A_0=1: outputs at A=1, B=C=0: all gates of FETs of MFMS1 are activated HIGH, while those of MFMS2 and MFMS3 are LOW. MFMS 1 is energized and the outputs of the sensor are force/moment signals acting on MFMS1.
3) Other two cases of A_1 and A_0 are similar with the above, except for choosing MFMS2 and MFMS3, respectively.

Moreover, to perform offset voltage cut off, each Wheatstone bridge is connected to a variable resistor (VR). By adjusting value of VR, output of the bridge is forced to zero (balance state of Wheatstone bridge) when the tactile system is at the free state (no load). Fig. 7 shows the implemented PCB (Printed Circuit Board) (35 mm in length x 15 mm in width x 1 mm in thickness) for the sensor which has two layers including placements of three MFMS chips, offset cut-off and multiplexer circuits, and an 11-pin connector as well.

V. PACKAGING

To perform the packaging for the sensing system, the following steps need to be done:

1) Attaching three MFMS chips on the PCB by using epoxy gel (Fig. 8(a)).

2) Implementing wire bonding connecting outputs of MFMS chips which are on the surfaces and the PCB (Fig. 8(b)).
3) Bonding electronic devices on the front and bottom layer of the PCB (Fig. 8(c)).
4) Inserting three silicon pillars (35 μm in length, 35 μm in width, and 2 mm in height). Inset picture shows the special clamp designed to hold and put the pillars into the MFMS chips (Fig. 8(d)).
5) Housing three MFMS chips by using a protection cap. Inset picture shows the set up for this purpose (Fig. 8(e)).
6) Putting three cured PDMS (Polydimethylsiloxane) soft tips, which have radius of 3 mm, on the cap to form a complete soft tactile sensing system with three sensory points (Fig. 8(f)).

In addition, to fulfill the entire system as illustrated in Fig. 2, we built a data acquisition software program by using Microsoft Visual C++6.0. This software is able to control the multiplexer circuit of the sensor via DAC (Digital to Analog Converter) PCI card, implement data acquisition from sensor's outputs via a ADC (Analog to Digital Convert) PCI card and digital filtering, and display all nine channels categorized into three groups corresponding to three sensing chip intuitively. The program also can be integrated into other controlling system as well. The sampling time is 0.05 s.

VI. Calibration

The calibration for this tactile sensing system requires two processes which specify two sensitivity matrices S, S' in equation (7) and (9)

Firstly, the calibrations of three MFMS chips was implemented after three MFMS chips had been attached onto the PCB during packaging process (Fig. 8(c)). This phase was performed using a micro-intender (SHIMADZU HMV-200, Japan) in which the sensor was put on a three-axis linear stage with resolution step of 2 μm, and under a micro hard tip (Fig. 10). For a sensing point, sensitivity matrix S in equation (7) needs to be obtained. At each calibration, program picked one specific MFMS chip by outputting corresponding control bits (A_0, A_1).

To calibrate the F_z, a predetermined force was applied to center of the sensing chip as illustrated in Fig. 10(a). This force was controlled to increase gradually to the desired value in 12 s, and keep that value for 10 s, and finally, release immediately. Fig. 10(b) shows the plots of all outputs when the applied force was 800 mN which nearly reaches the maximum value. We can observe that the signal of F_z has linear rise when the reference force increases, and gets unchanged when the force is kept; whereas M_x, M_y have slight changes around zero. In this critical case, the sensitivity of F_z is 0.029 mV/mN, while the crosstalk of M_y and M_x are 2.36 % and 9.26 %, respectively. These crosstalks are acceptable. After that, we changed the reference force from 0 to 500 mN sequently, and recorded the outputs. The calibration results can be seen quite linear in Fig. 11, in which the sensitivity S_{F_z}=0.029 mV/mN. Calibration for

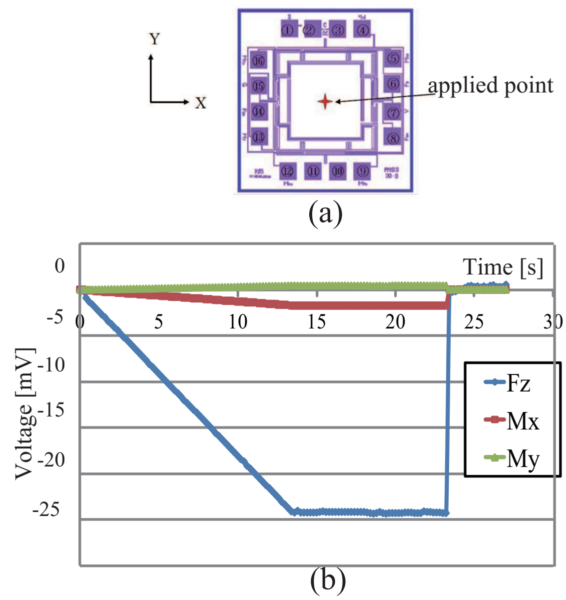


Fig. 10. Calibration of F_z: (a) Applied point of reference force on the MFMS chip. (b) Responses during calibration of one MFMS chip.

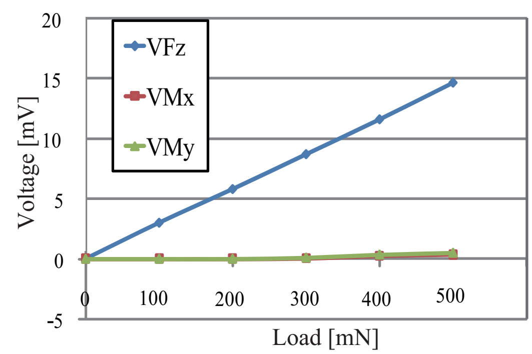


Fig. 11. Graphs of outputs of one MFMS chip under various loads for F_z calibration.

M_x, M_y are similar, therefore, we will only mention the calibration for M_x. Process of applying reference force is similar to that of F_z calibration, except that the applied point is 250 μm away from the center, and on the y-axis (Fig.12)(a). Fig.12(b) shows the outputs while calibrating. Basing on the outputs of M_x while the reference forces change, sensitivity S_{M_x} is 0.118 mV/Nμm. Similarly, S_{M_y} was calculated as 0.142 mV/Nμm. Because of the crosstalks among signals, sensitivity matrix S in equation (7) was modified and specified as followed:

$$S = \begin{pmatrix} 0.142 & 0.00742 & 0.00368 \\ 0.00116 & 0.118 & 0.0018 \\ 0.00926 & 0.00236 & 0.029 \end{pmatrix} \quad (10)$$

Secondly, the calibration of entire sensing system was carried out after finishing packaging. At this time, each sensing point had its soft hemispherical cap (Fig. 8(f)). In this process, the sensitivity matrix S' in equation (9) would

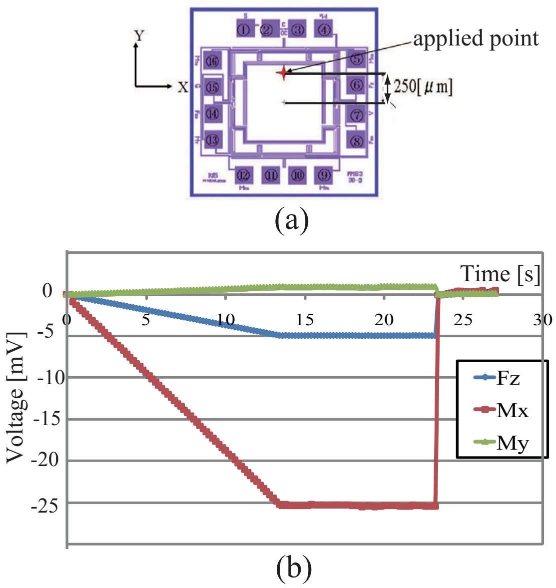


Fig. 12. Calibration of M_x: (a) Applied point of reference force on the MFMS chip with 250 μmm from x-axis. (b) Responses during calibration of one MFMS chip.

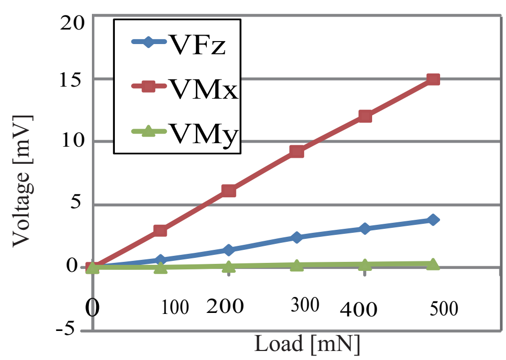


Fig. 13. Graphs of outputs of one MFMS chip under various loads for M_x calibration.

be obtained. The calibration of F_z' was performed by using INSTRON Micro Tester to generate reference vertical forces onto the top of the caps of three MFMS chips. Sensitivity to F_z' component is S_{Fz}'= 0.072 mV/mN at supplied voltahe of 2V. Calibration of M_x', and M_y' will be carried out by mounting two sensors onto two opposite fingers of a gripper, and make a gripping operation for each sensing point. The blocks with known weights were used to as gripped objects. From this calibration, the relation between weight of gripped objects and the output voltage will be assessed. This work is still ongoing, and will be reported soon.

VII. Conclusion

This paper has described our primary research on a complete sensor, with three soft compliant tactile sensing points, which is usable in artificial robot hands during manipulation tasks. Each sensing point is a micro MFMS chip utilizing MEMS technology and piezoresistive effectiveness which can detect simultaneously three components of force/moment around three axes. The outputs were calibrated with the computed sensitivity matrix; and the calibration showed linearity with the crosstalk in the critical condition (highest load) was about 9%. Moreover, with the design of on-chip electronic circuits, such as Wheatstone bridges, offset cut-off circuits, and multiplexer circuits, it helps to abate remarkably complications of outputting wirings and signal processing, as well as reduce the size.

The sensory fingertip with one sensing point was investigated as efficient in tactile and texture recognitions ([8]). Thus, the sensor with three sensing soft-contacting points will have more potential. This entire tactile sensor with three sensing points has a compact design with size of 35 mm x 15 mm x 5 mm. Each sensing point capped by soft hemisphere can detect force/moment up to 1 N. As a result, three compliant tactile sensing points distributed on a equilateral triangle are useful in complicated application which require border/edge detection, or in grasping small objects with complex surfaces.

Our on-going work still focuses on advancing the fabrication process and calibration to maintain stable and reliable operation of this tactile sensing system. Besides, object manipulating experiments using this sensing system will be carried out, such as grasping small complex objects or stretching textile pieces, to prove the potentials of this tactile sensor.

Acknowledgement

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