Fabrication of Tactile System with Three Sensing Points Using Micro Force/Moment Sensor

Van Anh Ho*, Yuki Takashima**, Dzung Viet Dao**, Susumu Sugiyama***, Shinichi Hirai*

Abstract: This paper describes our initial research in development of multi-axis fore/moment sensor with multi-sensing points which is used in robotic manipulator in small-scale applications. This sensor includes three MFMS (Micro Force Moment Sensing) chips which can generate three components of force/moment around three axes, an on-chip multiplexer circuit. This paper covers design and fabrication of this sensor.

Keywords : force/moment sensor, multiplexer, fingertip

1. Introduction

The sense of touch is an important component in field of dexterous manipulation. Without tactile feedback, small unmodeled errors can accumulate, causing failure in complex manipulation tasks (1). There have been many researches focusing on developing tactile sensing systems providing the complete force and moment at the end-effectors. These sensors cover from very small scale to large scale applications. Beccai *et al.* (2) fabricated a tactile sensing skin using miniaturized silicon-based sensor which can detect three components of external force up to single Newton. Engel (3) developed an integrated flexible tactile sensing skin which is not only sensitive with common surface characteristics such as frictional force, roughness; but also thermal conductivity, hardness, temperature. One of the problem of sensing array is wiring. Shinoda *et al.* (4) designed a flexible EMG (Electromyography) sensor array without any wiring by employed Two-Dimensional Communication skin to transfer both signal and electric power supply.

Our research focuses on the development of a soft tactile sensing system with three sensing points. The idea of using of three-sensing-point arrangement will be discussed later in this paper. Each sensing point is a Micro Force/Moment Sensing (MFMS) chip which can output one component of force (*Fz*) and two components of moment (*Mx, My*) by utilizing piezoresisting effectiveness and on-chip Wheatstone bridge circuits. Because of its large amount of signals, we designed an integrated multiplexer circuit using FETs (Field Effect Transistors) which permits decrement of number of outputting wires equaling with those of design with only one MFMS chip, while maintains the proper operation of the sensor. To establish a soft compliant encapsulation for the sensor, a polyurethane rubber hemisphere was cured and put up on three pillars. This paper will cover the idea, design, fabrication, and calibration for this sensor.

2. Overall Design

2.1 Idea

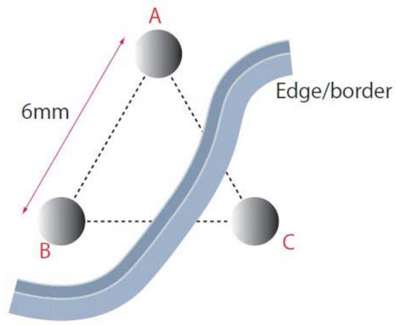

Fig. 1. Arrangement of three sensing points forms an equilateral triangle

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

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. By using this design, there would be no priority in specifying direction of moving fingertip on the object. Abilities of edge/border detection of three sensors are similar.

2.2 Design

Fig. 2 shows a flowchart of a complete tactile sensing system covers from hardware to soft ware. Three sensory points are three MFMS chips which will be reported in the next section. Besides,

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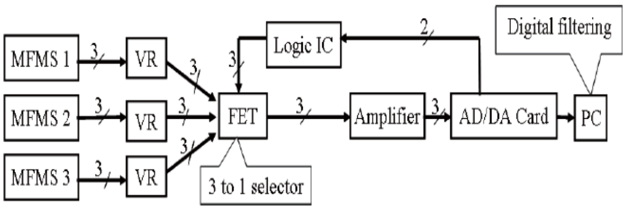


Fig. 2. Overview of the tactile system

three offset-cut-off circuits using variable resistors (VR) to get rid of offset values when three MFMS chips are at free states. All signals from three MFMS chips are led to 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 above modules are integrated on one PCB. 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. Besides, 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.

3. Micro Force/Moment Sensing Chip

As aforementioned, each sensing point of this sensor is a 3-DOF (Degree of Freedom) MFMS (Micro Force Moment Sensing) chip which can detect independently one component of force (*Fz*) and two components of moment (*My, Mz*). Fig. 2(a) shows the fabricated MFMS chip with dimension of 2mm x 2mm x 0.5mm. This MFMS has four beams form a rectangular with piezoresistors diffused at the suitable places on the beams. When an external force applies on the chip, it deforms the four beams and changes the resistances of the piezoresistors, which lead to changes in outputs of corresponding measurement circuits. Piezoresistors are designed on the surface of all beams, which are categorized into two types: ones detect longitudinal (normal) stresses and the others do shear stresses. The detailed principles of the operation can be found in (5). In this study, we configured construction of sensor so that it can output three components of force and moment which are *Fz, Mx*, and *My*, by arranging measurement circuits on the outer frame of the sensing chip. We hereafter explain the detection principle of *Fz*. *Mx*, and *My* have the similar principles. Fig. 2(b) shows three Wheatstone bridges which were designed beforehand on this MFMS chip, to convert change in resistance to an output voltage measuring the force *Fz*, as well as *Mx*, *My*. By integrating the Wheatstone bridges on chip, it requires no external transducer circuits which abate the complications in implementation. Fig. 2(b) shows a schematic of a half-bridge for measuring *Fz*, with two identical constant reference resistors R_{ref}, four piezoresistors R_{Fz1} through R_{Fz4}. These two reference resistors were placed in a non-stress area and chosen so that the bridge is balanced at non-stress state. When the resistances of piezoresistors R_{Fzi} are changed due to stress, the output voltage is expressed by:

$$V_{Fz} = \frac{r}{(1+r)^2}\left(\frac{\Delta R_{Fz1} + \Delta R_{Fz4}}{R_{Fz1} + R_{Fz4}} - \frac{\Delta R_{Fz2} + \Delta R_{Fz3}}{R_{Fz2} + R_{Fz3}}\right)V_{in} \quad (1)$$

where: $$r = \frac{R_{Fz1} + R_{Fz4}}{R_{Fz2} + R_{Fz3}} \quad (2)$$

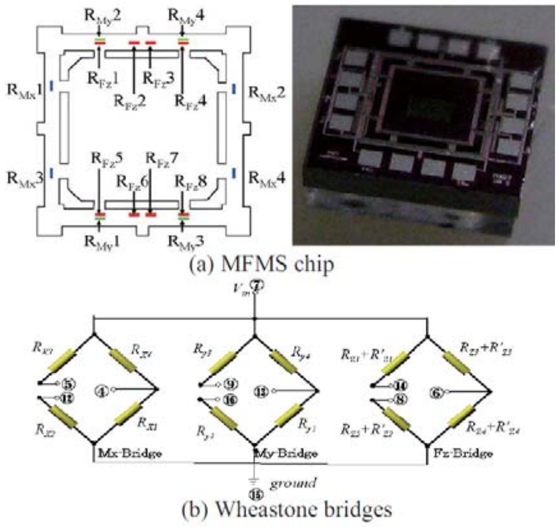


Fig. 3. Objective MFMS chip.

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

$$\sigma_{R_{Fz1}} = \sigma_{R_{Fz4}} = -\sigma_{R_{Fz2}} = -\sigma_{R_{Fz3}} \quad (3)$$

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

$$\Delta R_{Fz1} = \Delta R_{Fz4} = -\Delta R_{Fz2} = -\Delta R_{Fz3} \quad (4)$$

As a result, output voltage of the *Fz* can be shown as:

$$V_{outFz} = \frac{1}{2}\frac{\Delta R_{Fz1}}{\Delta R_{Fz1}} V_{in} \quad (5)$$

Besides, due to the symmetry of the arrangement of piezoresistors and the structure of the sensing chip, resistance change in each arm satisfied: $\Delta R_{My1} = -\Delta R_{My2} = -\Delta R_{My3} = \Delta R_{My4}$, therefore the *My*-bridge is still balanced. It happens similarly in case of *Mx*-bridge. As a result, crosstalk between each bridge is eliminated. Measurement principles are the similar for the *Mx*, and *My* Wheatstone bridges.

4. Electrical Design

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

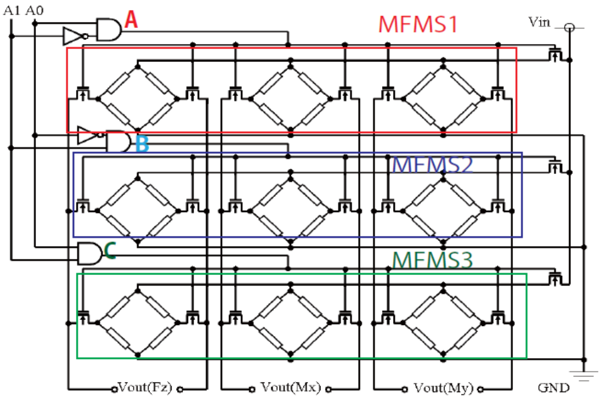
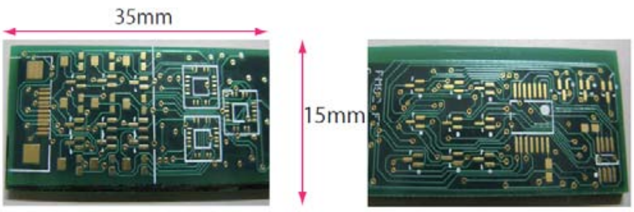


Fig. 4. Scheme of multiplexer circuit.



(a) Front view (b) Bottom view

Fig. 5 PCB (Printed Circuit Board) of the sensor

simplicity and compactness. Fig. 4 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. Besides, 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. 4) 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 A_0 and A_1. 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 are OFF states. There is no MFMS chip is selected, and no outputs as well.
2. A_1=0, A_0=0: 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. A_1=1, A_0=0: B=1, A=C=0. MFMS2 is energized and the outputs of the sensor are force/moment signals acting on MFMS2.
4. A_1=1, A_0=1: C=1, A=B=0. MFMS3 is energized and the outputs of the sensor are force/moment signals acting on MFMS3.

Besides, 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. 5 shows the implemented PCB (Printed Circuit Board) for the sensor which has two layers including placements of three MFMS chips, offset cut-off and multiplexer circuits, and 11-pin connector as well.

5. Fabrication

Detailed fabrication of the MFMS chip can be refered by (5). Following steps will describe the complete process of sensor fabrication:

1. Attaching three MFMS chips on the PCB by using epoxy gel (Fig. 6(a)).
2. Implementing wire bonding connecting outputs of MFMS chips which are on the surfaces and the PCB (Fig. 6(b)).
3. Bonding electronic devices on the front and bottom layer of the PCB (Fig. 6(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. 6(d)).
5. Housing three MFMS chips by using a protection cap. Inset picture shows the set up for this purpose (Fig. 6(e)).
6. Putting three cured PDMS (Polydimethylsiloxane) soft tips on the cap to form a complete soft tactile sensing system with three sensory points (Fig. 6(f)).

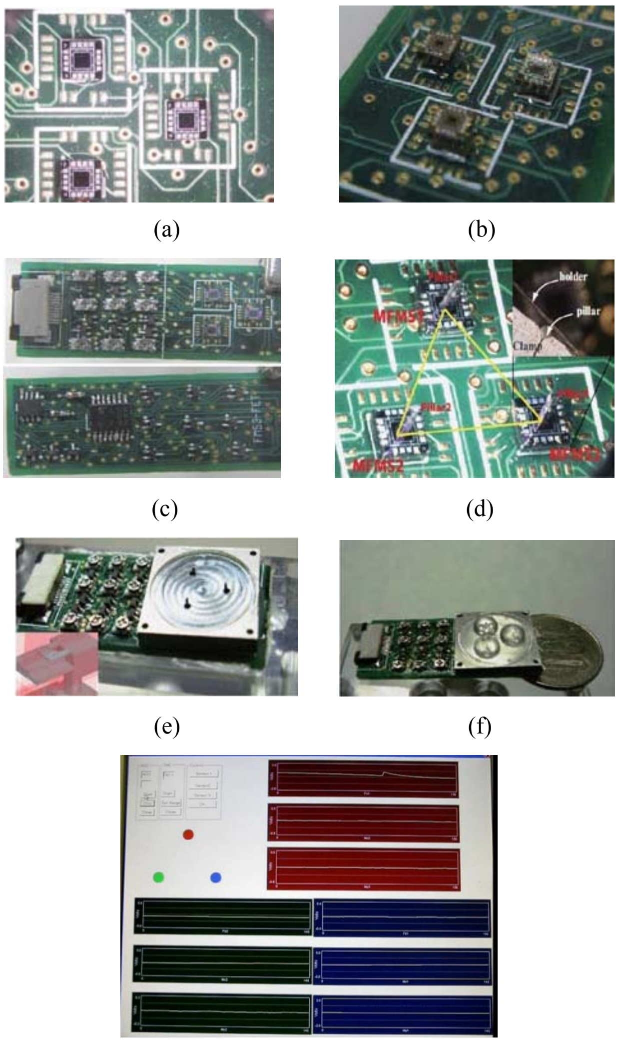
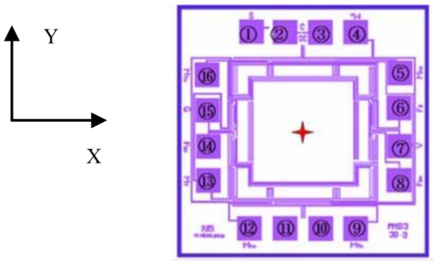
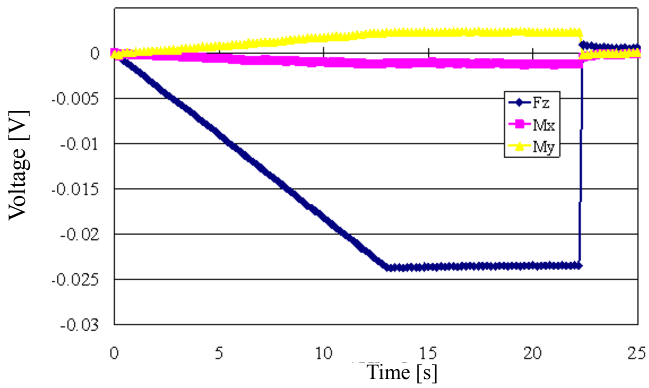

(a) (b) (c) (d) (e) (f) (g)

Fig. 6 Fabrication process of the sensor

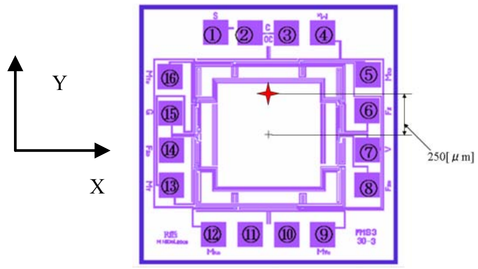


(a) Position of applied force

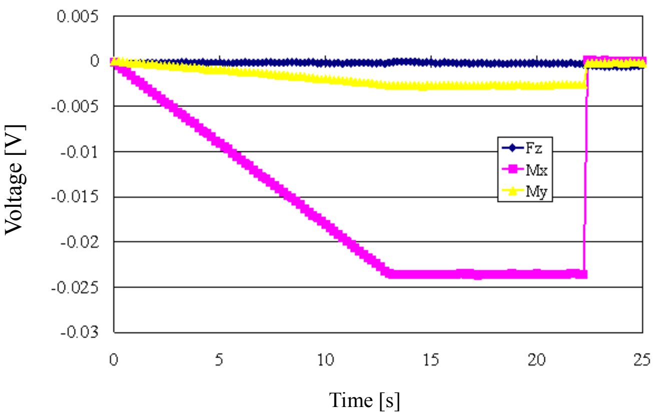


(b) Responses of the MFMS chip

Fig. 7. Calibration for *Fz*



(a) Position of applied force



(b) Responses of the MFMS chip

Fig. 8. Calibration of *Mx*

Moreover, a data acquisition program was also implemented by using Microsoft Visual C++ 6.0. This software interface is able to control the multiplexer circuit of the sensor via DAC (Digital to Analog Converter) PCI card, acquisite data from sensor via a ADC (Analog to Digital Convert) card, implement digital filtering, and display all nine signals of three sensing points on the screen (Fig. 6(g)). This program also can be integrated into other controlling system as well.

6. Calibration

To implement calibration for the sensor, we use a sclerometer to apply a predetermined force (800 μN) on each MFMS chip and measure the output voltages. The header of the sclerometer is programmed to apply an increasing force, keep unchanged for the amount of time afterward, and release quicly. Fig. 7(a) shows the calibration arrangement and output of *Fz* of the MFMS chip (Fig. 7(b)). The sensitivity for *Fz* is 0.029mV/mN. Fig. 8(a) shows the calibration arrangement and output of *Mx* of the MFMS chip (Fig. 8(b)). The header is applied to the point 250 μm away from the center point. The sensitivity for *Mx* is 0.118mV/N μm. The calibration for *My* was carried out simililarly.

7. Conclusions

This sensor with multi-sensing points is designed for a small-scaled fingertip in a robotic hand. This sensor is compact with total dimension is 35mm in length, 15mm in width and 2mm in thickness. Each sensing point can suffer a largest normal force up to 0.5N, and maximum moment of 0.5 Nmm. By providing diverse information of force/moment from distributed places, this sensor is useful in many application of robotic mannipulation. Further experiments in robotic manipulation will be carried out to show the potential of this sensor.

References

(1) J. S. Son, E. A. Monteverde, and R. D. Howe: “A Tactile Sensor for Localizing Transient Events in Manipulation”, Proc. IEEE Int. Conf. on Robotics and Automation, vol. 1, pp. 471-476, May 1994.

(2) L. Beccai, S. Roccella, L. Ascari, P. Vandastri, A. Sieber, M.~C. Carrozza, P. Dario: “evelopment and Experimental Analysis of aSoft Compliant Tactile Microsensor for Anthropormorphic Artificial Hand”, IEEE Transaction on Mechatronics, vol. 13, no. 13, April 2008.

(3) J. Engel, J. Chen, X. Wang, Z. Fan, C. Liu, D. Jones: “Technology Development of Integrated Multi-modal And Flexible Tactile Skin For Robotics Applications”, Proc. IEEE/RSJ Int. Conf. on Robotics System, vol. 3, pp. 2359-2364, Oct., 2003.

(4) Y. Makino, S. Ogawa, H. Shinoda, “Flexible EMG Sensor Array for Haptic Interface”, SICE Annual Conference, pp. 1468-1473, 2008.

(5) D. V. Dao, T. Toriyama, J. C. Wells, and S. Sugiyama, : Micro Force-moment Sensor with Six-Degree of Freedom , Proc. IEEE Int. Sym. on Micromechatronics and Human Science, 2001.