Sensors and Actuators A 215 (2014) 167–175

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

High-sensitivity triaxial tactile sensor with elastic microstructures pressing on piezoresistive cantilevers

Nguyen Thanh-Vinh[a,*], Nguyen Binh-Khiem[b], Hidetoshi Takahashi[b], Kiyoshi Matsumoto[b], Isao Shimoyama[a,b]

[a] *Department of Mechano-Informatics, Graduate School of Information Science and Technology, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan*
[b] *Information and Robot Technology Research Initiative, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan*

ARTICLE INFO

Article history:
Received 28 May 2013
Received in revised form 30 August 2013
Accepted 3 September 2013
Available online 13 September 2013

Keywords:
Triaxial tactile sensor
Piezoresistive cantilever
PDMS cap
Air cavity
High sensitivity

ABSTRACT

In this paper, we proposed a design to increase the sensitivity of a piezoresistive-type triaxial tactile sensor. Using conventional piezoresistive tactile sensors, in which the piezoresistive elements were completely embedded inside an elastic block, our proposed tactile sensor design features an air cavity underneath the piezoresistive elements. The cavity was created by pressing an elastic cap with microstructures onto the piezoresistive cantilevers of a sensor chip. We confirmed that the proposed design increased the sensitivity of the tactile sensor by approximately 150 times and 100 times in response to normal and lateral forces, respectively.

1. Introduction

MEMS-based three-dimensional tactile sensors have been developed for many applications, including in robotic systems, minimal invasive surgery, and the manipulation of robot hands [1,2]. Various types of tactile sensors have been proposed, which can be categorized as piezoresistive [3–9], piezoelectric [10,11], capacitive [12,13], and optical [14] sensors according to the transducer method employed.

The piezoresistive-type tactile sensor, which detects force using the resistance change of a piezoresistor due to deformation, has attracted significant attention. The piezoresistive tactile sensor has several advantages compared to other types of tactile sensors, including a high sensitivity, a high spatial resolution, a simple readout circuit, and well-established fabrication techniques. In this type of sensor, piezoresistive silicon elements are typically embedded inside a protective elastic body, e.g., polydimethylsiloxane (PDMS) [3–9]. This elastic body enables the soft interaction between the sensor and target object and prevents the fragile piezoresistive elements from fracturing. Piezoresistive sensing elements can be miniaturized to several micrometers and enable the measurement of delicate forces on the order of micronewtons [15–17]. However, once embedded inside an elastic body, the deformation of the piezoresistive elements is restricted by the surrounding elastomer, and thus, the sensitivity of the sensor decreases [1].

In this paper, we propose the structure of a PDMS cap with convex microstructures pressing on the piezoresistive cantilevers, as shown in Fig. 1(a), to increase the sensitivity of the piezoresistive tactile sensor while maintaining the elastic cover. Our proposed structure features a cavity under each cantilever, which provides more room for the cantilever to deform (Fig. 1(b)). Therefore, under the same pressure, the deformation of the cantilevers in our sensor will be greater than in the case where the cantilevers are completely confined inside an elastic body. In other words, our sensor achieves a higher sensing sensitivity.

The PDMS cap functions as a cover that protects the cantilevers and interacts with target objects. The forces acting on the surface of the PDMS cap are transmitted to the cantilevers through the microstructures. The prototype sensor using a PDMS cap with pyramid-shaped microstructures was reported in MEMS 2013 [18]. In this paper, sensors with three types of convex microstructures, namely, pyramid-shape, pillar-shape, and ring-shape, were fabricated and evaluated. The sensitivities of these sensors were compared with that of a sensor in which the cantilevers were completely embedded inside the PDMS.

* Corresponding author at: Rm. 81B, Engineering Building 2, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan. Tel.: +81 3 5841 6318; fax: +81 3 3818 0835.
E-mail address: vinh@leopard.t.u-tokyo.ac.jp (N. Thanh-Vinh).

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http://dx.doi.org/10.1016/j.sna.2013.09.002

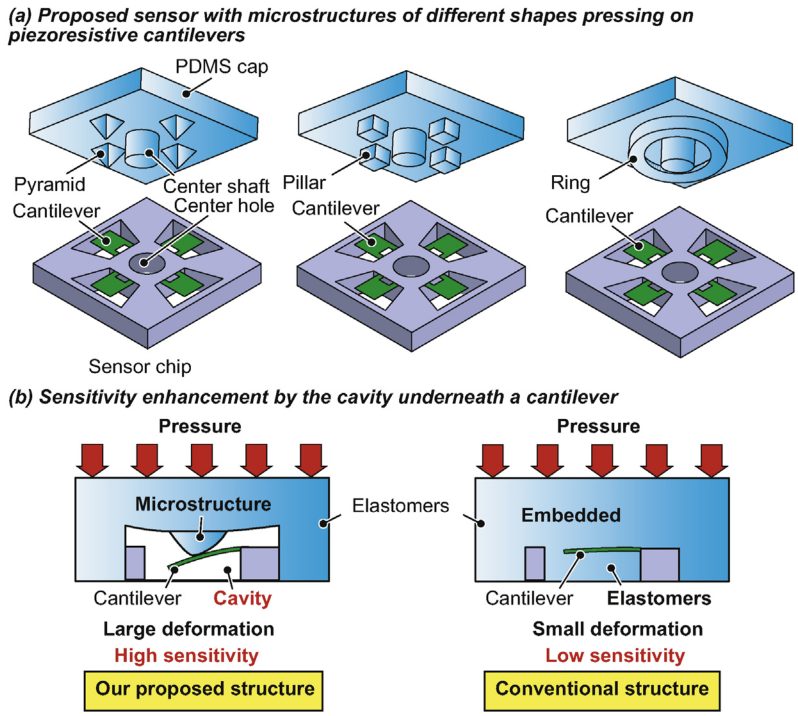

Fig. 1. (a) Conceptual sketch of the proposed three-dimensional tactile sensors. Each sensor device consists of a PDMS cap having pyramid-, pillar-, or ring-shaped microstructures and a sensor chip with four piezoresistive cantilevers. (b) The method used to increase the sensitivity of our proposed sensor compared to the conventional method.

Furthermore, by using the structure in which four cantilevers are aligned with the four microstructures of the PDMS cap, we demonstrated the capability of the proposed sensor to detect the forces in both the normal and lateral directions.

2. Sensing principle

The normal force- and lateral force-sensing principles, for example, in the case of a PDMS cap with pyramid-shaped microstructures, are shown in Fig. 2. Notice that we design our sensors so that, even in the load-free state, the pyramids are pre-pressed on the cantilevers, causing the initial deformation of each cantilever.

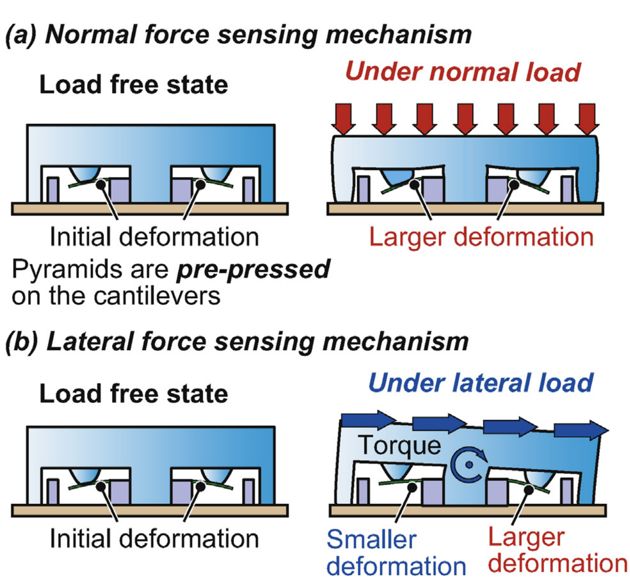

Fig. 2. Sensing mechanism of the proposed sensor using pyramid-shaped microstructures. Note that in the load-free state, the pyramids are still pre-pressed on the cantilever.

2.1. Normal force-sensing principle

As shown in Fig. 2(a), when a normal force is applied to the PDMS cap, the deformation of all four cantilevers becomes larger than their initial deformations. Thus, we can detect the applied normal force from the average of the resistance change of the four cantilevers.

2.2. Lateral force-sensing principle

As shown in Fig. 2(b), when a force in the lateral direction is applied to the surface of the PDMS cap, there is a torque around the center pillar of the PDMS cap. This torque causes the surface of the PDMS cap to rotate slightly. As a result, one cantilever will have a smaller deformation and the opposite cantilever will have a larger deformation compared to their initial deformations. The force in the lateral direction can be established based on the difference between the resistance changes of these two cantilevers.

3. Design

The design parameters of the sensor chip and PDMS caps are shown in Fig. 3(a). The dimensions of the chip are $2\,mm \times 2\,mm \times 0.3\,mm$. The sensor chip consists of a hole in the center with diameter of $300\,\mu m$. Four cantilevers are arranged in a cross shape around the hole. The size of a cantilever is $125\,\mu m \times 100\,\mu m \times 5\,\mu m$. The piezoresistors are formed on the surface of the two hinges of the cantilever where the strain is concentrated when the cantilever bends. The size of each hinge is $25\,\mu m \times 25\,\mu m \times 5\,\mu m$.

The design of the PDMS cap with pyramid-shaped microstructures is shown in Fig. 3(b). The size of the PDMS cap is $10\,mm \times 10\,mm \times 1\,mm$. A cylinder-shaped shaft with a diameter