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Design and Modeling of a New Tactile Sensor Based on Membrane Deflection

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Abstract: The designed sensor can detect 2D surface texture image, contact-force, and softness of the sensed object. It consists of a chamber for pneumatic actuation and a membrane with a mesa structure. The sensing mechanism is the contact deformation effect of a membrane. Determination of the contact force and softness of sensed object is based on the amount and variations of the out-of-plane deflection at the center of a circular membrane. This versatility facilitates the use of the sensor in smart applications where tactile information is used to create intelligent system. The proposed sensor is suitable for using in medical applications, especially in minimally invasive surgery (MIS).

Key words: Tactile sensor, contact force, softness, deflection, membrane

INTRODUCTION

Tactile sensing is the detection and measurement of the spatial distribution of forces perpendicular to a predetermined sensory area, and the subsequent interpretation of spatial information. It is an area of MEMS research that has the potential to have an impact on a large number of industries and disciplines. Key among these is the application to robotics in medicine and industrial automation[1]. Robust, reliable tactile feedback of forces and torques, contact shape and location, and dynamic slip sensing are required for dexterous, dynamic gripping and manipulation by robots and by humans through haptic interfaces[1]. Lack of such suitable commercial tactile sensors will limit development in robotic handling of soft, fragile or irregular objects. Several types of tactile sensors have already been proposed for handling objects in robotics and automation systems. They can handle soft and fragile materials only with great difficulty[2]. In different biomedical engineering and medical robotics applications, tactile sensors can be used to sense a wide range of stimuli. This includes detecting the presence or absence of a grasped tissue/object or even mapping a complete tactile image[3-5]. Artificial palpation is another important application of tactile sensors.

Normally, in order to improve the efficiency of these types of sensors, an array of sensors is utilized[6, 7]. Force and position signatures are the two factors that can provide a great deal of information about the state of gripping or manipulation of a biological tissue[8]. Additionally, tactile and visual sensing is of great importance in different types of surgeries[9]. Minimally invasive surgery (MIS) is now being widely used as one of the most preferred choices for various types of operations[10-12]. In MIS, any inhibitions on the surgeon's sensory abilities might lead to undesirable results[13]. MIS has many advantages, including reducing trauma, alleviating pain, requiring smaller incisions, faster recovery time and reducing post-operation complications[14,15]. However, MIS decreases the tactile sensory perception of the surgeon. This effect is more pronounced during grasping or manipulation of biological tissues (i.e., veins, arteries, bones, etc.). In this regard, measuring the magnitude of the applied forces applied by the surgeon through the endoscopic graspers results in safer handling of biological tissues [16]. Controlled manipulation tasks are among the maneuvers in which the ability to feel the tissues are very crucial[17]. The need to detect various tactile properties (such as stiffness, temperature, and surface texture) justifies the key role of tactile sensing which is currently missing in MIS[9, 18, 19].

One of the disadvantages of working with surgical tools, e.g., commercial endoscopic graspers used in MIS, is that these tools do not convey sufficient feeling to the surgeon's hands. Here, the surgeon does not have any tactile feedback so that he/she can manipulate the biological tissues safely and avoid accidental cutting or damaging the healthy parts. To reduce this possibility, tactile sensors can be incorporated into the endoscopic graspers[20, 21].

There are operation sites in human body that are otherwise difficult to see in order to examine or operate

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on. As a result, only relying on the visual tools is not sufficient to obtain satisfactory results [22].

Below we discuss the most recent advances in tactile sensors in different types of medical industries, especially for detecting the softness of biological tissue will be presented.

Softness is an important parameter in determining the physical properties of living tissue. Considerable biomedical attention has centered on the mechanical properties of living tissues at the single cell level. The Young's modulus of zona pellucida of bovine ovum was calculated using micro-tactile sensor fabricated and PZT material[23]. The stiffness of the cartilage of the human femoral condyles was measured via an ultrasonic tactile sensor under arthroscopic control[24]. The tactile sensor was useful for determining the intraoperative stiffness of healthy and diseased human cartilage in all grades. This research work describes an approach of studying the dynamic, information rich, molecular structure of the ultimate smart interface, i.e., human skin, by coupling the advances in biological, microsystems, and information technology. The development of milli-robotic tools for remote, MIS, is reported. It describes the limitations of current surgical practice and the technological and scientific issues involved in building a telesurgical workstation[25]. A new tactile sensor system has been developed for accurate measurement of myocardial stiffness in situ[26]. Piezoresistive sensors, applied to the fingertips of nonsensate fingers, were used for the detection of touch and pressure in four patients with recent median nerve repairs, and in one patient using a myoelectric prosthesis[27]. The design, fabrication, testing, and mathematical modeling of a semiconductor microstrain gauge endoscopic tactile sensor have been investigated[13]. The sensor can measure, with reasonable accuracy, the magnitude and the position of an applied load on the grasper.

In this paper, we propose a new type of tactile sensor that can detect both the contact force and the softness of an object. Our proposed sensor offers the following combination of characteristics:

1-Mechanical flexibility and robustness
2-Relatively low processing temperature (<350° C)
3-Low fabrication complexity
4-Improved strain transfer from membrane to strain gauges or other measurement devices
5-Decrease fabrication cost because of its simplicity

The shortcomings of most of the current designs are mainly related to the complexity of the systems used. The major advantage of the system proposed in this paper is the simplicity and robustness of the design.

MATERIALS AND METHODS

Sensed Objects: A review of related literature shows that the variations of compliance and stiffness are quite large in different biological tissues. For instance, the Young's modulus of elasticity is about 0.11 MPa for the pig spleen, while it is about 4.0 MPa for the pig liver. The same conclusion describes the case for human tissues[28]. To cover this wide range of values, we consider the different values of stiffness of silicon rubber with variable thickness.

2D Surface Texture Image Detection: This sensor can be used to sense a diverse range of stimulus ranging from detecting the presence or absence of a grasped object to a complete tactile image. Figure 1 shows an array of two elements of our tactile sensor. Each sensor consists of a membrane with a mesa at the center and a chamber for pneumatic actuation. A salient feature of our tactile sensing is its ability to encode and decode the shape of objects.

When the tactile sensor array comes in contact with an object that has a bumpy surface, some of the mesa structures on the membrane push inwards and as a result of it, the system can detect the presence or absence of object above each of elements. So, we can save a 2D surface texture image of the object.

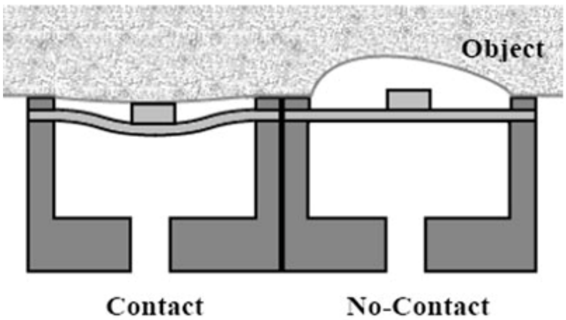

Fig. 1: An array of two elements for detecting contact force distribution and surface texture image

Contact-Force Estimation: The structure of the estimating contact-force is shown in Fig. 1. When the mesa of membrane comes in contact with an object, the normal force or uniform pressure from it causes inward deformation of the membrane. Therefore, by determining the displacement at the center of the membrane and according to the mechanical properties of it, we can measure the amount of normal force or the uniform pressure actuating on it.

Softness Detection: In this mode, the contacting mesa elements are pneumatically driven against the object (Fig. 2).

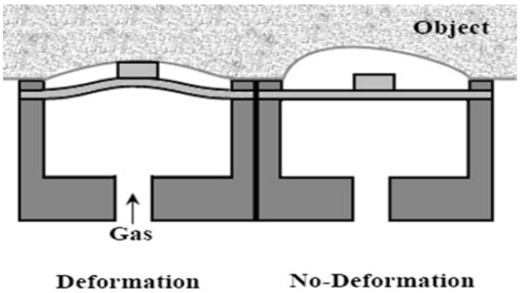

Fig. 2: A schematic of tactile sensor for detecting softness distribution

The contact regions of the object are deformed according to the driving force of the mesa element and the softness of the object. Therefore, we can detect the softness of the object by measuring the relationship between the deflection of the membrane and the actuation force of it.

Sensor Principle and Design

Device Specification: The device has a cylindrical shape and a result it caused to simplify the problem and reduce the amount of calculation. The radius of membrane is 2 cm and it is attached on a rigid cylinder which has a port for gas supply and exhaust. The thickness of membrane is 100 µm and the radius of mesa is 0.5 cm with a thickness about 150 µm. Two series of theoretical and numerical tests have been performed in this study. We designed the sensor specification to detect the touch of a human finger.

Theoretical Analysis: We modeled the tactile sensor theoretically as shown in Fig. 3 and assumed that the membrane and contacted object are elastic materials.

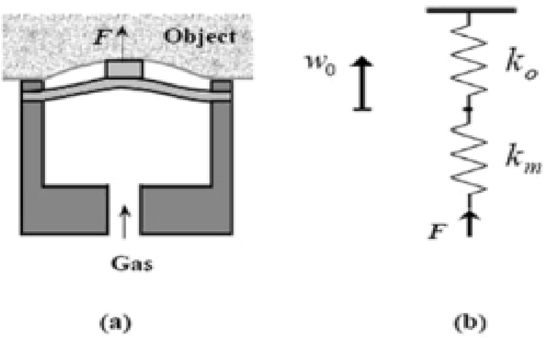

Fig. 3: a) Functional model of the sensing element. b) Simulation of functionality of the sensing element.

The relationship between the deformation w_0 (displacement at the center of the membrane or mesa) of the object and applied force *F* is given by:

$$F = (k_m + k_o)w_0 \tag{1}$$

where k_m and k_o are the elastic constants of the membrane and object, respectively[29]. To obtain k_o, we used a contact model in which the surface profile of the object changes according to the pushing depth of the mesa structure toward the object. The theoretical model of a single-layer circular membrane is shown in Fig. 4.

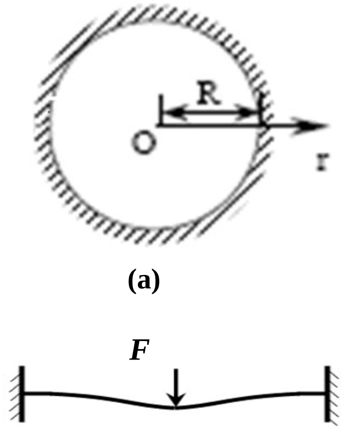

Fig. 4: Theoretical model. (a) Top view and (b) Front view

The problem of axisymmetric large deformation of circular membrane is one with practical significance. For a single-layer circular membranes under the concentrated force from the large deformation theory of them, the solution for out-of-plane deflections (OPD) can be expressed as[30]:

$$(\frac{w_0}{h})^3 = [1-(\frac{1-3\nu}{4})^{1/3}]^3 \frac{4R^2}{(1+\nu)\pi Eh^4} F \tag{2}$$

when $\nu = 1/3$,

$$(\frac{w_0}{h})^3 = \frac{3R^2}{\pi Eh^4} F \tag{3}$$

In the above formulas w_0 is OPD (out-of-plane deflection) of membrane, *R* is radius of membrane, *h* is thickness of membrane, ν is Poisson's ratio, *E* is elastic modulus, and *F* is applied force at central point.

Numerical Analysis: The second series of tests were performed to stimulate the mechanical responses of sensor numerically. The finite element modeling of sensor shown in Fig. 5 for which a commercial finite element analysis software package (ANSYS, version 10.0) was employed.

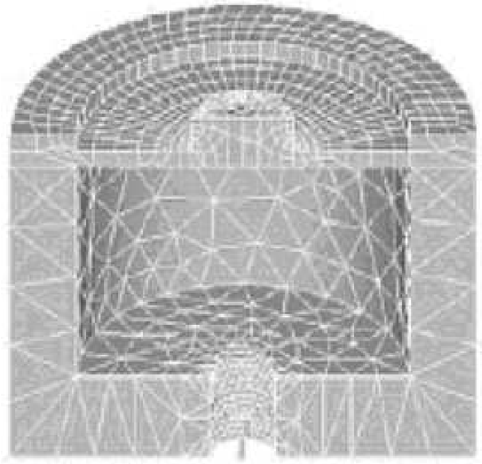

Fig. 5: Finite element modeling of the sensor.

Table 1 shows typical specifications of the sensor element, modeled in the finite element method.

Table 1: Specifications of the modeled sensor

2 cm (inner radius) 3 cm (outer radius) 5 cm (height)	Device (cylindrical)
2 cm (radius) 100 μm (thickness)	Membrane
0.5 cm (radius) 150 μm (thickness)	Mesa
0.33	ν (Poisson's ratio)
30 MPa	E (Elastic modulus)
10-1000 N/m	k_m (Elastic constant)

RESULTS AND DISCUSSION

The theoretical and numerical results have been in good agreement. We investigated the deformation at the center of mesa and found that it changes with variations of applied force and the thickness of membrane. Fig. 6 shows the variations of OPD of membrane with the constant radius and unique force (0.1N) at different thicknesses.

As a result of applied force at the center of membrane, we have an out-of-plane deflection on it. Figure 7 demonstrates the deformation or out-of-plane deflections of membrane according to the variations of applied force.

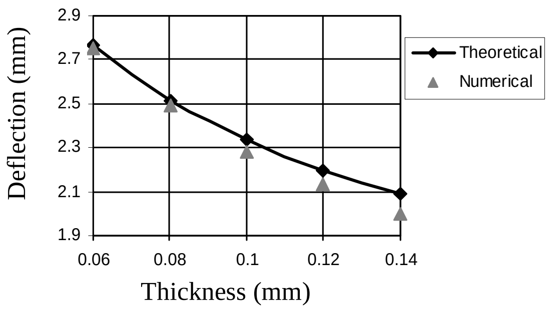

Fig. 6: Variations of out-of-plane deflections vs. different thicknesses.

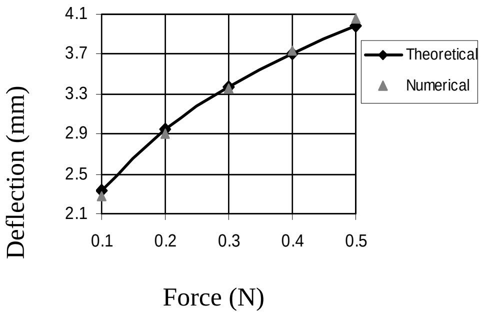

Fig. 7: Variations of out-of-plane deflections vs. different applied forces.

Table 2 shows the values of numerical and theoretical analysis and the good agreement of them.

Table 2: Comparison of numerical and theoretical analysis

(N) F	Theoretical W_0 (mm)	Numerical (mm) W_0	% Error
0.1	2.335	2.277	2.48
0.2	2.942	2.910	1.08
0.3	3.368	3.363	0.15
0.4	3.707	3.732	-0.67
0.5	3.993	4.051	-1.45

Figure 8 shows a typical sample of numerical analysis. In this sample, the radius of membrane is 2 cm, the thickness of membrane is 100 μm and the applied force is 0.5N. It shows that the maximum amount of deflection occurs at the center of the membrane.

Fig. 8: Deflection of the membrane due to the applied force

The contact regions of the object are deformed according to the driving force of the mesa element and the softness of the object (Fig. 9). Therefore, we can detect the softness distribution of the object by measuring the relationship between the deflection of the membrane and the actuation force of the elements.

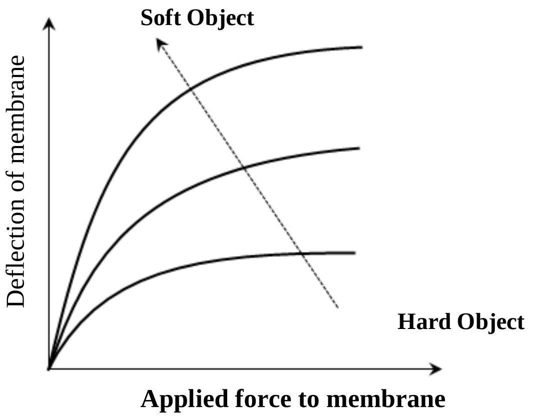

Fig. 9: Relationship between the deflection of the membrane and applied force

We investigated the changes of the deformation with k_o and obtained the following results:

a) $k_o << k_m$: In this region, the elasticity of the object is much smaller than the elasticity of the membrane. As a result, in this region, the sensor cannot sense the softness of the object and the variation of it.

b) $k_o >> k_m$: In this region, the elasticity of the object is too large compared to the membrane. In this manner, the deflection of the membrane is very small and with increasing the softness of object, the amount of deflection declines to zero. As a result, in this region, the membrane of the sensor cannot deform and the sensor cannot detect the softness or changes of it.

c) $k_o \approx k_m$: In this region, the mechanical properties of object are similar to those of the membrane. Therefore, the amount of deflection of membrane is related to softness of the object and this amount changes with the variations of softness. As a result, in this region, the sensor can detect the softness of the object according to the membrane deflection, against the amount of deflection in the same condition when membrane does not have any contact with the object.

We conclude that in order to detect a change in the softness of the touched object, the elastic constant of the membrane should be almost the same as that of the touched object. Figure 10 shows how the deformation of the object changes with elastic constant of object (k_o).

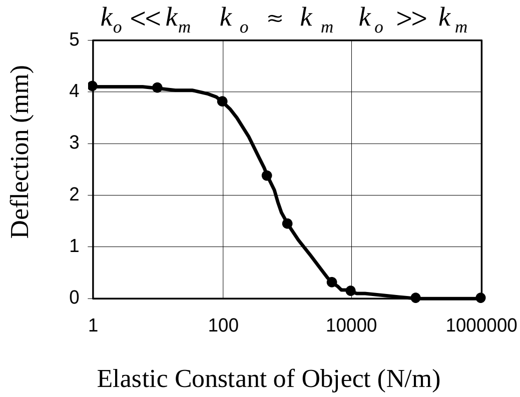

Fig. 10: Membrane deflection vs. elastic constant of object

CONCLUSION

The demonstrated polymer-based tactile sensor is a major step towards realizing sensors that can provide robots with direct tactile feedback similar to the biological sense of touch. We proposed a new type of tactile sensor that can detect both the contact force and softness of an object. We analyzed theoretically and numerically the operation of the tactile sensor. This device can be made from robust, flexible polymers that can be used to directly touch objects, and serve as a skin on robotic actuators. Providing such information to robotics opens new areas to development and exploration.

A major advantage of the designed system is that it can be easily miniaturized and micromachined. As a result, it could be mass-produced at low cost and even be disposable. Because of its biological compatibility, the designed sensor has two main applications, one in MIS and one in artificial palpation.

In the future, we are planning to:

1) Construct the device's sensor element and get experimental results for comparing with theoretical results.

2) Use different kinds of transducers for determining the deflection of membrane and choose the best of them according to the output results.

3) Make simple digital interface to a controller.

4) Determine the softness of several different materials (silicon with different softness).

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