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Effects of the elastic cover on tactile sensor arrays

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Abstract

Tactile sensors are composed of two substantial parts, the sensory structure and its cover. The characteristics of a sensor are fundamentally set by the sensor design, but are also essentially modified by the elastic cover on top. In this paper we analyze the pure mechanical information-coding effects of the sheltering rubber layer, applied on single-crystalline silicon 3D-force sensors, capable to detect both normal and shear forces. We give instructions on how to enhance the sensor's sensitivity by mimicking human tactile perception with introducing hair- and fingerprint-like elements to the sensor design.

Keywords: Tactile sensor; Elastic cover; Semi-infinite elastic model; Receptive field

1. Introduction

Artificial tactile sensors are simple models of the peripheral part of human touch. Sensors are analogues of the mechanoreceptors while the protective coating is similar to the skin. Besides protecting the sensors from damage, this elastic medium acts as an information-coding layer, and thereby plays a crucial role in determining the sensor's characteristics.

The theory of the mechanical effects arising in the elastic cover was discussed by several groups. Refs. [1] and [2] investigates the role of the skin in the neural coding of primate tactile manipulation, while [3] and [4] analyzes the mechanical effects for utilization in future artificial tactile sensors. Nevertheless, precise experiments about the feasibility of the theoretical predictions on artificial sensors have not yet been reported.

In this paper we will check the validity and the limitations of the continuum-mechanical model [1], by providing experimental data, measured by a piezoresistive force-sensor array, capable of resolving all three vector components of the surface load. We also extend the capability of the sensors by applying various coatings, each with a different geometry. As a biological motivation, we try to mimic the function of the hairy skin and the fingerprints to enhance sensitivity to certain indentation types.

2. Sensor design

The sensor array (Fig. 1) is built up from monocrystalline-silicon sensory elements, all consisting of a central plate, suspended by four bridges over an etched cavity.

Each of the four bridges includes a p^+ piezoresistor that is used as an independent strain gauge. The two shear and one normal component of the surface load can be reconstructed from these four channels. The detailed description of the structure was recently reported [5].

The active sensory region was covered with silicon rubber[1] either by simply pouring the viscous material on the top, or by attaching a pre-made rubber layer with a well-defined thickness to the sensor, glued with some of the viscous material itself. In both methods, the elastomer forms a coating on the suspended membrane and infiltrates the cavity. In the former the thickness is purely controlled by the viscosity, while in the latter it can be chosen as preferred. Moreover, the latter method provides more freedom to form elastic coatings of various shapes.

3. Continuum mechanics

In order to characterize the covered sensor's performance, we need to calculate the stress and strain fields arising at the

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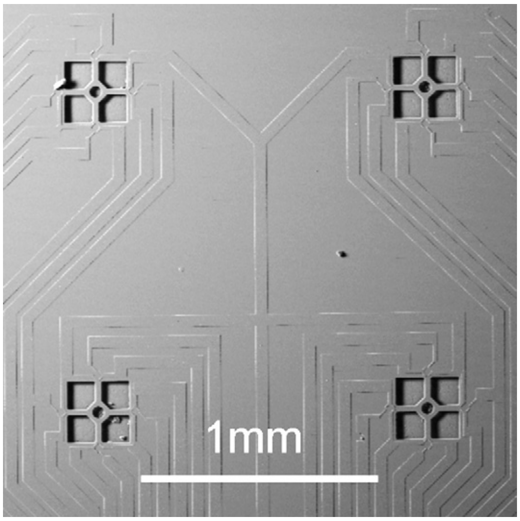

Fig. 1. Scanning-electron view of the 2 × 2 sensor array. All four sensory elements consist of a suspended cross-like bridge and four piezoresistors at the suspension points. Taxels (tactile pixels) are spaced 1.5 mm.

bottom of the elastic layer, as a result of the surface load. We will use the semi-infinite elastic model [6] and make the following assumptions: (1) the elastic material is linear, homogenous and treated as semi-infinite, (2) the rubber is incompressible—Poisson's ratio is 0.5, (3) the sensor measures the strain in the rubber, appearing at the center point of the piezoresistors.

First we analyze point loading. The equations below are derived from [6], and will be used as a theoretical reference for the strain distribution (Fig. 2(b)):

$$\begin{pmatrix} \gamma_x \\ \gamma_y \\ \varepsilon_z \end{pmatrix} = \frac{3(Qx + Fz)}{4\pi E(x^2 + y^2 + z^2)^{5/2}} \begin{pmatrix} 3xz \\ 3yz \\ x^2 + y^2 - 2z^2 \end{pmatrix} \tag{1}$$

where F is the normal, Q is one shear component of the load (the other is set to zero now for simplicity, reducing the 3D analysis to 2D), E the Young modulus, x, y and z are coordinates in the rubber (z points towards the sensor), γ_x, γ_y and ε_z are the two shear and one normal component of the strain tensor acting on the z plane.

4. Signal conditioning

An efficient and simple method is described in [7] for reconstructing the stress field at the sensor surface inside the rubber, by using the four bridge voltages. In contrast to the proposed method, we found that the deformation of the sensor bridges is a function of the strain field and not the stress. The structure of the equations, however, remains unchanged:

$$\gamma_x = \alpha_s(\Delta V_{\mathrm{left}} - \Delta V_{\mathrm{right}}), \qquad \gamma_y = \alpha_s(\Delta V_{\mathrm{down}} - \Delta V_{\mathrm{up}}),$$
$$\varepsilon_z = \frac{\alpha_n}{2}(\Delta V_{\mathrm{left}} + \Delta V_{\mathrm{right}} + \Delta V_{\mathrm{down}} + \Delta V_{\mathrm{up}}) \tag{2}$$

where γ_x, γ_y and ε_z are the strain tensor components, ΔV_i represents the measured voltage change, the α linear constants (shear and normal) contain the piezoresistive coefficients and all the information about the geometry of the sensor and the signal amplification.

5. Receptive-field measurements

In order to check the feasibility of the semi-infinite model, we carried out different experiments. First we measured the strain profile in the case of constant, normal loading. A sharp needle was slowly moved across the sensor surface along the x-axis (from left to right), and voltages were saved at 30 Hz. Measured strain components calculated with (2) are shown in Fig. 2(a), while theoretical components from (1) are shown in Fig. 2(b). In both cases Young modulus was set to 2.4 MPa, as calculated from the rubber's Shore A hardness of 45. Rubber thickness was 180 μm, total indentation force was 10 mN. Other measurement parameters are given in Table 1.

Lacking a detailed analysis of the geometry and the amplification factors, we arbitrarily choose 1/mV for the α_s and α_n constants. However, we are only interested now in the relative amplitudes of the strain components, so this simplification has no practical consequences.

To estimate the similarity of the two curves shown in Fig. 2, we measured some of their basic properties. For simplicity, we

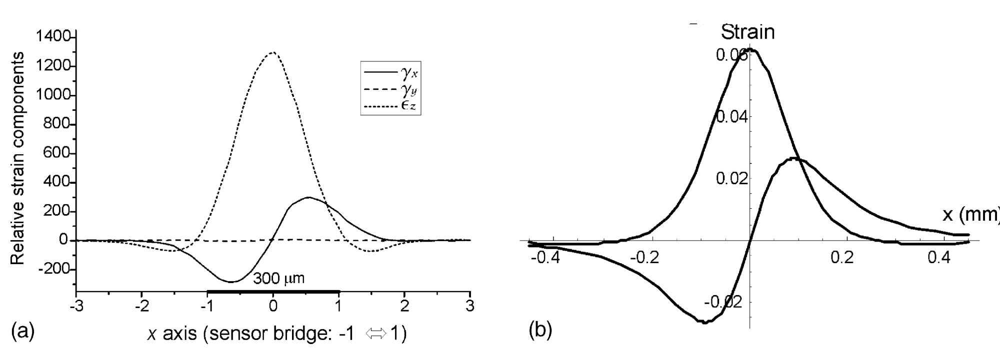

Fig. 2. Measured (a) and theoretical (b) strain components in the case of a point load, moving along the x-axis. On (a) the x-axis is scaled to the sensor size, the y-axis is presenting relative values only (as described in detail in the text). The general shape of the measured curves highly resembles that of the theoretical curves.