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Soft dielectrics for capacitive sensing in robot skins: Performance of different elastomer types

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ABSTRACT

In a capacitive tactile sensor the dielectric layer plays an important role: both its electrical and mechanical properties affect the capacitance variation and the sensor response in terms of sensitivity, since the deformation ability of the dielectric layer allows for the detection of small pressures, and spatial resolution, since the dielectric layer acts as a low-pass spatial filter decreasing the spatial resolution. In this work we comparatively evaluate the effect of different elastomers on the performance of a capacitive sensor designed to cover large areas of a robot body. In particular, we compare the sensitivity, the spatial resolution and the durability of the sensor using foams, bulk elastomers and high permittivity composites.

1. Introduction

In the past decades, the role of tactile sensing in Robotics has received steadily increasing attention [1]. Tactile sensing is expected to broaden the perceptual capabilities of robots and to enhance their cognitive and motion capabilities in unstructured environments. In recent years, thanks to technological advancements on the miniaturization of electronic components, a renovated interest is being focused on *robot skins*, i.e., large-scale tactile surfaces able to cover wide areas of a robot body [2–5]. A fundamental design aspect is to precisely characterize the response of tactile elements (i.e., *taxels*) with respect to design choices related to geometrical sensor layout and employed materials. On the basis of this characterization, the sensor can be customized to better address robot tasks.

The mechanical characteristics of the dielectric layer impact on the overall skin performance and, in particular, on sensitivity, spatial resolution, and weight. Elastomers are selected as dielectric layers in capacitive sensors for their high compliance, their ability to act as a protective cover and, in case of manipulation tasks, for the increased friction they enable. The choice of the most appropriate elastomer is not an easy task. In this article we present the response of a capacitive sensor designed to cover large areas of a robot body, comparing different elastomers as dielectric layer. We analyse the sensor sensitivity obtained from foam and bulk elastomers, and high-permittivity composites. The aim is to investigate how the mechanical and electrical properties of the dielectric layer affect the sensor performance.

2. Related work

2.1. Piezo-capacitive sensing principle

Capacitance-based tactile sensors have been widely used for large-scale robot skins [1]. Forces exerted on a robot skin produce variations in the capacitance values of tactile elements (i.e., taxels). The differential capacitance measurement relies on an estimate of the difference between the capacitance values in the nominal and contact cases:

$$\Delta C = C_p - C_n = \epsilon_0 \epsilon_r A \frac{d_n - d_p}{d_p d_n}, \tag{1}$$

where C_p and d_p are, respectively, the capacitance value and the elastomer thickness in the *contact* case (i.e., when a pressure is exerted over the taxel), and C_n and d_n correspond to the *non contact* or nominal case. In order to exploit capacitance-based transduction, it is necessary to maximize the sensor response range. According

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to Eq. (1), the dielectric constant, taxel area, the nominal thickness of the dielectric, and its mechanical properties are fundamental design parameters.

Much work has been carried out to correlate specific robot tasks with the physical properties characterizing tactile sensors [6–10]. However, the analysis has been mainly focused on identifying materials whose response characteristics resemble at best that of human fingertips [11]. According to [8–10], four are the main desirable properties of dielectric materials for robot skin in fingertips: *compliance* allows the dielectric material to yield elastically when even small forces (e.g., less than 1 N) are applied, thereby enhancing the robot performance when executing force-controlled tasks [6,7]; *hysteresis* enforces the capability of the dielectric material to absorb energy generated when big forces are applied as the result of impact or catching events [9,7]; *conformability* allows the robot to reach more stable grasping configurations, since the amount of fingertip surface in physical contact with the grasped object is maximized on average [7]; *friction* maximizes the likelihood of avoiding slippage [12,13].

The above considerations tend to neglect the employed transduction mode, the thickness and dielectric constant of the dielectric as well as the actual taxel area. In a piezo-capacitive sensor, the hysteresis can seriously affect the repeatability of the measurements, since the force distribution is usually estimated from the deformation of the elastic medium [14].

Shimojo et al. [15] analysed the low-pass spatial filtering characteristics of the elastic cover of a tactile sensor, arguing that its spatial resolution depends on the cover's thickness and stiffness. Vásárhelyi et al. [16] analysed the mechanical information-coding effects of a rubber layer applied on single-crystalline silicon 3D force sensors capable of detecting normal and shear forces. Their work refers only to a specific elastomer and is focused mainly on the correlation between the performance of the tactile sensor and the geometrical characteristics of the elastic medium (e.g., on the use of ridges to detect tangential force components).

The literature in this field does not offer well-defined procedures and commonly accepted benchmarks on how the mechanical, geometrical and electrical properties of different layers can affect the *overall* response of a tactile sensor. Taking inspiration from [17], here we characterize the sensor's overall performance using the following sensitivity function:

$$S = \frac{\Delta C}{\Delta P}, \tag{2}$$

where ΔC is the measured variation in capacitance between the *non contact* and *contact* cases (Eq. (1)) and ΔP is the related variation of the applied pressure. The main difference with respect to the definition proposed in [17] is the lack of the coefficient inversely weighting C_n. Since, in our case, C_n differs for each taxel, we prefer to characterize an independent measurement of the capacitance variation in response to a given pressure.

2.2. Increasing the dielectric permittivity

As shown by Eq. (1), the dielectric permittivity can be thought of as a sensor design parameter [18]: the sensor response range (i.e., the difference between the largest and smallest possible values of the quantity measured by the sensor) depends on the taxel area. If a reduction of the taxel area is required to increase the spatial resolution, a high value of dielectric permittivity allows for maintaining the same sensor response range.

In general, elastomers are characterized by a low dielectric permittivity. In the literature, different methods have been discussed to increase it [19], namely the composite approach [20,21], the blend approach [22,23] the electric-field structuring approach [24,25] and the synthesis of new macromolecules [26]. Of particular interest for our purposes, are the composites obtained by loading an elastomer matrix with high dielectric permittivity fillers, such as titanium dioxide (TiO_2), strontium titanate ($SrTiO_3$) and lead magnesium niobate-lead titanate (PMN-PT).

In particular, Carpi and De Rossi [27] showed that the dispersion of titanium dioxide powder in a silicone dielectric elastomer resulted in a lower elastic modulus within certain range of strain and a higher dielectric permittivity. Paik and colleagues [28] discussed the effects of barium titanate ($BaTiO_3$) and $SrTiO_3$ powders on the dielectric constant of epoxy/$BaTiO_3$($SrTiO_3$) composite for embedded capacitor films. Gallone et al. [29] showed that a PMN-PT ferroelectric powder can be used to develop a composite based on a silicone elastomer matrix with improved dielectric permittivity. In this work, we exploit the same approach reported in [27,29] for the production of different composites, as described later in the paper.

3. Target scenario and requirements

3.1. Reference robot skin

In this work we considered the reference robot skin technology described in [3,4], which is based on a tactile sensor consisting of a 3-layer structure (Fig. 1a). A bottom layer (made of a flexible Printed Circuit Board – fPCB) was divided in a number of interconnected 3 cm side triangular modules that enforce coverage compliance with respect to robot body parts with varying curvatures (Fig. 1b and c). Each module hosted 12 circular taxels of a 4 mm diameter as well as (on the opposite side, not shown in the Figure) the read-out electronics for converting capacitance values to 16 bit digital signals (this was accomplished by the Capacitance to Digital Converter chip AD7147 from Analogue Devices, excited at 250 kHz). An intermediate layer constitutes the compliant dielectric medium for the capacitive sensor. Different candidate elastomers were compared, as detailed later on. A top layer, made of a ground plane, forms the second electrode of the capacitor. In particular, an electrically conductive Lycra fabric was glued to the elastomer and connected to ground. This configuration allowed us to assume the same sensor response when objects with different electrical conductivity were in contact. Furthermore, a reduction of the electronic noise was achieved.

When a pressure was exerted on the tactile surface, the conductive Lycra layer got closer to the taxel pads on the fPCB. The CDC chip of each module measured the variation in capacitance of all the taxels in the module. Each measurement was then sent to a central processing unit through a serial I^2C bus.

3.2. Requirements

Human–robot interaction tasks involving the robot sense of touch require the detection of contact events involving both people and the environment surrounding the robot. It is possible to identify two different broad classes of contacts on the basis of pressure range [18]: on the one hand, the *gentle touch* class is characterized by contact pressures in the 0–10 KPa range; on the other hand, the *manipulation-like touch* class involves pressures in the range 10–100 KPa. Therefore, any tactile sensor to be used in real-world robot tasks must be (i) compliant enough to detect gentle touch contact events, i.e., be responsive to forces whose magnitude is less than 1 N, and (ii) characterized by a ΔC such to allow for the detection of manipulation-like forces.

In tactile sensors employing the capacitance-based transduction principle, the *tendency to be elastically deformed* as a consequence of the application of a force depends solely on the employed