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Polymer micromachined multimodal tactile sensors

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Abstract

We present the design, fabrication process, and characterization of a multimodal tactile sensor made of polymer materials and metal thin film sensors. The multimodal sensor can detect the hardness, thermal conductivity, temperature, and surface contour of a contact object for comprehensive evaluation of contact objects and events. Polymer materials reduce the cost and the fabrication complexity for the sensor skin, while increasing mechanical flexibility and robustness. Experimental tests show the skin is able to differentiate between objects using measured properties.

Keywords: Hardness; Thermal conductivity; Sensor skin; Tactile; Polyimide

1. Introduction

Microelectromechanical systems (MEMS) have the potential to produce high-density sensor arrays integrated with signal processing electronics. Due to this capability, research is being conducted to develop MEMS sensors that mimic the form and functionality of biological sensing systems [1–7]. In this paper, we present an effort to develop an MEMS multimodal tactile sensor skin that mimics certain design and functional aspects of biological skins.

Biological tactile sensors, such as mechanoreceptors found in the skin of a human finger, can simultaneously detect hardness, temperature, thermal conductivity, and surface roughness for multimodal, comprehensive evaluation of the contact object and event [1]. To gain such rich tactile information in real time, the human tactile skin has a variety of specialized structures (Fig. 1) such as fast responding Meissner's and Pacinian corpuscles for sensing vibration and touch, slow Ruffini endings and Merkel's discs for sensing deformation and touch, Kraus' end bulb thermoreceptors for temperature sensing, and hair follicles for sensing flow, proximity, and touch [8]. Our current work is inspired by two aspects of these biological sensing skins: multimodal sensing ability using specialized sensing structures and flexible, robust materials.

Robust, reliable multimodal tactile feedback of forces, torques, thermal properties, mechanical properties, contact shape and location, and dynamic slip sensing are required for dexterous and assured gripping and manipulation of objects by robots [1]. Future applications of engineered tactile sensors include robotics in medicine for minimally invasive and micro surgeries, in the military for dangerous and delicate tasks, and in industry for automation. However, existing state of the art macro and MEMS-scale tactile sensors still cannot satisfy these proposed applications due to limited data gathering capabilities, low deformability, insufficient mechanical robustness, and general packaging difficulties. The ability of MEMS technology to integrate a variety of sensing structures in a very small space will be critical to solving this engineering challenge.

Macro-scale tactile sensing devices made with conductive rubber force sensitive resistors (FSRs) are widely used in robotics research. These sensors generally require serial or manual assembly, provide highly non-linear response, and provide limited independent sensing modes [9,10]. Conductive rubber FSRs have been integrated with robotic appendages to provide tactile information. In one type, 'x' and 'y' column electrodes are stitched into an FSR rubber sheet which is then sewn around the robotic fingers [11]. A more advanced robotic hand and tactile sensor using FSRs and an industrial fabrication process has been demonstrated by Kawasaki et al. in cooperation with the Nitta Corporation [12]. FSR arrays for normal force measurement are now commercially available on flexible but not conformal

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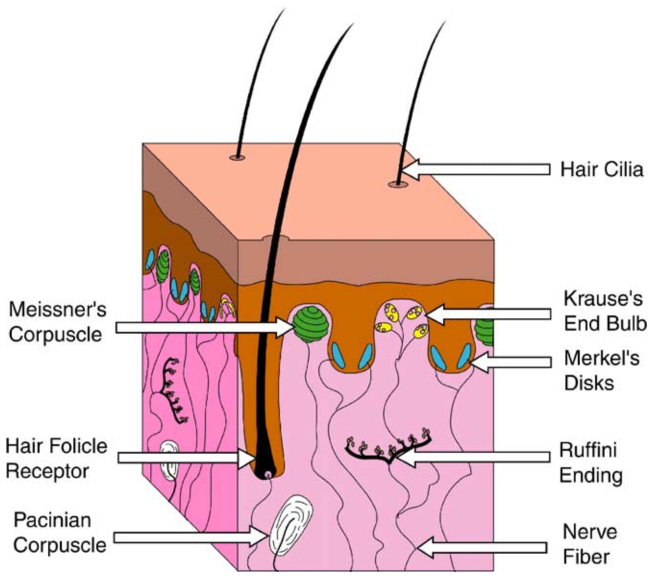

Fig. 1. Schematic cross-section of biological skin, showing Meissner's, Pacinian, and Ruffini corpuscles as well as Merkel's discs for sensing deformation and touch, thermoreceptors for sensing temperature, as well as hair cilia and follicles for sensing flow and touch.

polymer substrates from companies such as Tekscan. Lack of a micromachining method for such materials has limited sensor sizes to approximately 1 mm^2 for each array element. Other researchers have tried to incorporate discrete sensors directly in polymeric materials, for example, by embedding off-the-shelf accelerometers and piezoelectric strips in a molded rubber finger to measure vibration caused by dynamic interaction with surface texture [13].

MEMS micromachined tactile sensing work to date has mainly focused on silicon-based sensors that use piezoresistive [14–16] or capacitive sensing [17–19]. These sensors have been realized with bulk and surface micromachining methods. Polymer-based devices have also been demonstrated that use piezoelectric polymer films [20–22] such as polyvinylidene fluoride (PVDF) for sensing. A number of other techniques such as ultrasonic [23], pneumatic [24], and hybrid resistive [25] sensing have been explored to a limited degree. Several groups have embedded silicon sensing elements in polymer skins [26,27], or covered silicon-based devices in a protective polymer layer [14,17,19]. However, devices that incorporate brittle sensing elements such as silicon-based diaphragms or piezoresistors, even embedded in protective polymers, have not proven to be a reliable interface between a robotic manipulator and the manipulated object.

Recently, work has been directed towards combining multiple tactile sensing modes, such as contact force and hardness, or normal and shear forces [9,10,24]. However, these approaches rely on a single sensing structure with a coupled response to different sensing modalities and requiring a carefully controlled sensing sequence to sequentially measure contact object parameters. For example, in the case of FSRs the sensor must be brought into contact without applying a load in order to measure thermal properties independently of mechanical properties. This done, a calibrated known load can be applied to assess contact object hardness, texture, and other mechanical properties [28]. In addition, these rubbers have a non-linear response to force as well as a large and non-linear thermal coefficient of resistance (TCR), making unstructured sensing difficult.

In this paper, we present a first polymer-based sensor skin with multiple independent sensing modalities, including the ability to sense the hardness, the thermal conductivity, the temperature, and the surface profile of an object. Unlike previous multimodal approaches based on FSRs, the presented multimodal polymer skin uses specialized sensing structures to perform various sensing functions, similar to the design of the human skin. The polymer MEMS skin offers the following combination of characteristics:

1. Mechanical flexibility and robustness.
2. Low fabrication complexity with the potential for continuous roll-to-roll fabrication.
3. Specialized sensing elements for sensing multiple physical phenomena grouped in sensor nodes.
4. Relatively low processing temperature ($<350\,^{\circ}$C).
5. Improved strain transfer from membrane to strain gauges due to direct deposition of sensors on polymer skin rather than on intermediate adhesive layers [29].

2. Multimodal skin design

To meet the goal of multimodal sensing, a different approach is taken in our work, where a dedicated sensor is primarily responsible for each phenomenon of interest. The skin consists of an array of sensor nodes, each composed of four distinct sensors: a reference nickel resistance temperature device (RTD) for temperature measurement and compensation, a gold heater and nickel RTD pair for thermal conductivity measurement, a membrane with a nickel–chrome alloy (NiCr, 80:20 wt.%) strain-gauge for contact force and hardness sensing, and a NiCr strain gauge reference contact force and hardness sensor (Fig. 2a). In addition, the contour of the skin is sensed in an integrated fashion using NiCr strain gauges dispersed between sensory nodes (Fig. 2b). When the skin is mounted on a curved or compliant surface (e.g., a robotic finger tip), the spatial relation of sensor nodes is mapped to coordinate manipulation in 3D space. The multimodal sensor skin is built on a flexible DuPont Kapton HN200 polyimide sheet and utilizes simple metal thin film resistors to serve a variety of specialized sensing functions. Polyimides represent a family of polymers (Kapton and HD4000 included) that exhibit outstanding mechanical, chemical, and thermal properties as a result of their cyclic chain bonding structure [30]. To the best of our knowledge, the development, integration, and characterization of thermal conductivity, hardness, and curvature sen-