A POLYMER-BASED MEMS MULTI-MODAL SENSORY SKIN

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Introduction

One of the most important senses for performing varied complex and precise tasks autonomously or remotely via robotics is the sense of touch. Tactile feedback from the human skin provides a multitude of information, including force, temperature, hardness, texture, and thermal conductivity. To date, robots do not have the sensing capability to provide them with an equivalent sense of "touch".

Devices that incorporate brittle sensing elements such as silicon-based diaphragms or piezoresistors, even embedded in protective polymers, cannot be used as the interface "skin" between a robotic manipulator and the manipulated object. Devices made with pressure sensitive rubbers that can withstand contact have been presented, but require serial manual assembly, are based on rigid substrates or provide limited independent sensing modes. In an effort to overcome these limitations, we present a tough, monolithic polymer-based sensing skin that incorporates a number of metal film sensors.

Multi-Modal Sensing Skin. The reported device is fabricated on DuPont Kapton HN200 2-mil-thick polyimide film. The use of a polymer substrate allows flexibility, robustness, and low material cost, with the ability to build additional polymer structures on the film. Our device is comprised of four distinct sensors: a reference nickel RTD for temperature measurement and compensation, a gold heater and nickel RTD pair for thermal conductivity measurement, a membrane NiCr strain-gauge based contact force and hardness sensor, and a reference contact hardness sensor (Fig 1a). In addition, the contour of the skin is sensed (although not presented here) in an integrated fashion using NiCr strain gauges dispersed between sensory nodes (Fig 1b). 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. To the best of our knowledge, the development, integration, and characterization of thermal conductivity, hardness, and curvature sensors using polymer micromachining has not been previously achieved.

Temperature Sensing. Incorporated in our sensing skin is a nickel RTD (Fig 1a) that is used to measure the temperature of the operating environment as well as contact objects. This information is important for temperature compensation of the measurements of the other sensors as well as providing contact object information.

Hardness Sensing. Existing micromachined hardness sensors require the applied force be known, a known calibrated integral actuator force, or observe a changing resonant frequency under ultrasonic vibration. The required assumptions, complexity, and size limitations of such approaches do not lend themselves to a distributed multi-modal skin. We have developed a passive hardness sensor that does not rely on actuation or knowledge of contact force.

The device consists of a measurement sensor on a polymer diaphragm and reference sensor on the bulk polymer substrate. Both sensors include a contact mesa as shown in Figure 3 with strain gauges situated on the periphery of these mesas. The square measurement diaphragm (Fig 3a) has a relatively low stiffness and for a given maximum central displacement requires a uniform pressure according to clamped-clamped plate theory as shown in Eq. 1.

\[
q_{\text{plate}} = \frac{z_{\text{max}} E t^3}{(0.0138)b^4} \]

(1)

Where \(z_{\text{max}}\) is the peak vertical deflection in the center of the diaphragm, \(q_{\text{plate}}\) is the pressure applied to the plate, \(b\) is the length of the square sides, \(E\) is the material modulus, and \(t\) is the plate thickness.

The reference sensor does not use a diaphragm; rather the contact mesa and strain gauges are positioned over full thickness bulk polymer (Fig 3b). The stiffness of the bulk reference sensor is thus much higher than the measurement diaphragm. The sensor requires a uniform pressure for a given deflection according to Eq. 2.

\[
q_{\text{bulk}} = \frac{z_{\text{max}} E}{(2.24) a (1 - V^2)} \]

(2)

Where \(V\) is the bulk material Poisson’s ratio, \(a\) is the contact mesa width, and \(q_{\text{bulk}}\) is the pressure applied to the bulk sensor contact mesa. This model assumes that the reference sensor behaves like a semi-infinite block under a uniform pressure over the area of the contact mesa. With a film thickness of 50µm and deflections on the order of 0.1-1.0µm this assumption may not be valid and further modeling required.

When the sensor skin is in contact with an object, changes in resistance are observed at both the measurement and reference sensor strain gauges. The measured resistance changes are converted to a peak deflection \((z_{\text{peak}})\) with calibrated resistance versus displacement data and used to find the apparent pressures \(q_{\text{meas}}\) and \(q_{\text{bulk}}\) with Eq 1 and 2. Under device operation it is found that the contact object hardness is proportional to the ratio of apparent pressures.

Measurement of contact forces can also be performed using the same polymer diaphragm and bulk sensors. Based on the known geometry of the devices, the pressures can be equated to normal force. The differential stiffness of the two sensors allows two different ranges of contact forces to be measured.

Thermal Conductivity Sensing. The thermal conductivity sensor operates by observing the changing resistance of the nickel RTD in response to an input to the gold heater. The thermal conductivity of a contacting object is a useful measure for object discrimination, and in concert with other sensing modes can expand the capabilities of the overall skin by helping to distinguish between equally “hard” objects for example.

To accomplish this measurement, the demonstrated sensor consists of a gold heater situated near a nickel RTD (Fig 1a). When not in contact with an object, the only route for the heat input of the heater to reach the RTD is through the polyimide substrate and the surrounding air. When an object comes in contact with the sensor, the low efficiency heat path through the air is replaced by solid conduction, changing the character of the signal measured at the nickel RTD. With a square wave voltage input to the heater, the temperature of the RTD can be modeled as a simple first order system according to Eq 3.

\[
T_{\text{RTD}}(t) = 1 - e^{-t/\tau} \]

(3)

Where \(\tau\) is the time constant of the first order system, giving a measure of how quickly the system responds to an input. The time constant of the RTD temperature is found to be a function of contact object thermal conductivity.
This method is relatively computationally intensive but was found to correlate well to contact object thermal conductivity.

**Results and Discussion**

**Temperature Calibration.** We first characterize the TCR of each sensor to allow temperature compensation via calibrating the reference Ni RTD. The skin is placed on a hotplate equipped with a surface mounted thermocouple and heated. The changes in resistance with temperature are observed and plotted for each sensor to calculate the base metal TCR. Values were found to be 2385ppm/˚C for Ni, 1013ppm/˚C for Au, and –25ppm/˚C for NiCr. Au wiring is used throughout the device due to low resistivity and ability to withstand products of polyamic acid imidization reactions such as acetic acid that attack other metals such as copper.

**Hardness Testing.** Testing of the hardness sensor pair is accomplished by placing a number of reference samples of sorbothane and polyurethane rubber with known hardnesses ranging from 10 to 80 Shore A pressed onto the sensor skin using a fixed mass (147g). The change in resistance of each sensor is converted to an equivalent displacement using calibration data. Calibration data is generated by measuring the change in resistance of the measurement membrane sensor and the bulk reference sensor in response to a known normal displacement provided by a micromanipulator probe coupled to a precision linearly variable differential transformer (LVDT).

Displacement data is equated to equivalent pressure using Eq. 1 and 2. The proportionality between pressure ratio and object hardness is shown in Figure 4. A large amount of scatter was observed in the hardness data as can be seen in the figure. We attribute this to the surface roughness of the rubber samples, as the surface features are on order with the contact mesas (100um). The polyimide (HD Microsystems, HD4000) contact mesas micromachined onto the bulk Kapton film are observed to have excellent adhesion to the bulk polyimide and perform as if monolithic.

**Thermal Conductivity Testing.** Characterization of the performance of the thermal conductivity sensor is performed at room temperature (~22°C) by inputting a 0-2VDC square wave at 0.3 Hz to the gold heater and measuring the resulting change in resistance of the nearby Ni RTD. The resistance of the RTD is sampled at 10 Hz using an Agilent 34401A multi-meter and GPIB interface.

The sensor should behave as a first order system with a time constant related to the object thermal conductivity. Figure 5 shows the result of testing, where contact objects of various thermal conductivities (nylon 6, soda-lime glass, single crystal silicon, 300-series stainless steel, aluminum, and ambient air) were placed in contact with the sensor skin and the time constant of the resulting RTD signal was obtained through curve fitting. It is observed that the time constant decreases and the step response of the RTD temperature is faster with increasing thermal conductivity. Scatter is observed and expected due to changes in contact configuration from test to test due to surface roughness.

The relationship between object thermal conductivity and time constant is found to be approximately logarithmic based on a curve fit of Figure 5. As a result attempts to formulate a simple electrical analogue model were not successful. We also hypothesized that the steady state temperature reached by the RTD would correlate to object properties but testing showed that the relationship was not monotonic with thermal conductivity, diffusivity, or other characteristic value.

**References**