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A Distributed Pressure Sensor For Biomechanical Measurements

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1 Introduction

In precision manipulation, interaction between the hand and grasped object is mediated by pressure distributions across the fingertips. These pressure distributions determine the mechanical behavior of the hand-object system, and quantitative measurement promises to improve our understanding of the mechanics of manipulation [Lee and Kim, 1991]. The central nervous system receives pressure distribution information from specialized mechanoreceptive nerve endings found in great density in the finger tip skin. Pressure distribution measurements reveal local stimulus conditions at these end organs, which can be correlated with microneurographic measurements of nerve response to infer transduction mechanisms.

Forces within the range of $0 - 3$ N have been shown to be particularly important during grasping and manipulation [Westling and Johansson, 1987]. When these forces are applied using a flat indentor, a configuration used in many manipulation operations like grasping a flat-sided box, the corresponding maximum pressures are typically less than 50 kPa. As we are interested in the local conditions above a mechanoreceptive nerve ending, it is desirable to have a spatial resolution comparable to that of its receptive field ($\approx 3-4$ mm). In addition, this spatial resolution must be provided within a sensor area which covers the entire fingerpad (typically between $1-2$ cm^2). A rapid temporal response is also needed to examine the dynamics of the fingerpad (the mechanoreceptors respond to frequencies as high as 1 kHz). These latter three factors are typically traded-off in any realistic sensor design [Howe and Cutkosky, 1992].

Unfortunately, commercially available sensors that measure pressure distributions have been developed for applications such as gait, knee and wrist analysis [Hara et al., 1992, Hughes et al., 1993, Pavlovic et al., 1993, Werner et al., 1995] for pressure ranges (greater than 1 MPa) far above those used in dexterous manipulation. Even the most sensitive Fuji pre-scale film is not sufficiently sensitive, as well as providing only peak measurements. In addition, the technologies commonly used in the construction of commercially available sensors, such as conductive rubbers and conductive inks, suffer from a number of performance limitations, including hysteresis, contact noise and low sensitivity [Howe and Cutkosky, 1992]. These limitations make them undesirable for our application.

This technical brief describes a pressure distribution sensor for performing dynamic fingerpad measurements. The performance specifications reported here are also intended to provide a quantitative benchmark for comparison of pressure distribution sensors.

2 Device Design

The design is based on capacitive tactile array sensors developed for robotic applications. These sensors consist of orthogonal layers of copper strips separated by a dielectric. Applying pressure to the sensor's upper surface forces the copper strips closer together, increasing the capacitance at the cross-points, each of which forms one array element. The change in the measured capacitance of the element is closely proportional to the local pressure above it [Fearing, 1990].

The device described here is a flat 8 element by 8 element sensor array with an elemental spacing of 2 mm (see Figure 1). This design uses thin strips of silicone rubber to separate the layers of copper strips, with air as the dielectric. The array was covered with a 2.0 mm layer of elastomer (GE RTV 110 Silicone Rubber Adhesive Sealant) to protect it from mechanical damage. It was electrically shielded by grounding the rigid back plane on which it was mounted, and by embedding a thin layer of gold foil in the elastomer which was also grounded. The sensor is characterized assuming both the rigid back plane and protective elastomer as integral components of the device.

The sensing electronics are based on a design by Fearing [Fearing, 1990]. The elements are serially scanned by applying a 200 kHz sine wave to the column of an element and demodulating the output from the corresponding row. All unused rows and columns are grounded to reduce cross talk.

3 Sensor Performance

The key performance parameters for a distributed pressure sensor for biomechanical applications are the time response, the spatial response and the absolute sensitivity, usually limited by noise, hysteresis and linearity [Howe and Cutkosky, 1992]. Low noise is particularly important when examining fingers as the pressures of interest are often small (≤ 50 kPa). The noise of the sensing elements was gaussian with a standard deviation of 0.5 kPa (≈ 1.2 g per element).

Low hysteresis is essential for accurate measurements and linearity is desirable for ease of calibration and data analysis. Performance was evaluated by examining the correspondence between the capacitance of each element and the local pressure using a pneumatic static pressure chamber. Pressure was increased from 0 to 60 kPa in steps of 10 kPa, then decreased in the same manner. A silicon pressure transducer (SenSym 142SC15D: maximum deviation from linearity of 0.75%, typical repeatability and hysteresis of 0.2%) recorded the chamber pressure. The responses of the elements fit a linear response with a worst case element mean squared error (m.s.e.) of 0.4% and a maximum deviation from linearity of 4%. Hysteresis was below the noise level. As a verification of the gain calibration procedure, the sum of the calibrated pressure measurements during a contact experiment was compared to the net force measured with a separate force sensor with a resulting m.s.e. = 0.2% (see Figure 2).

Viscoelastic properties can limit the time response of the sensor, even with fast electronics. The response time was measured by rapidly removing a brass weight from the surface of the sensor (using a lever mechanism) to examine the step response. Two weights were used:

one corresponding to pressures at approximately mid-range (i.e., $\approx$ 25 kPa) and the other to pressures near the maximum (i.e., $\approx$ 50 kPa). The responses for all elements were, on average, greater than 88% of their final values in less than two samples (i.e., 10 msec) and typically at 85% within the first sample (i.e., 5 msec). There were no discernible differences with variation in load, suggesting that the time response is linear.

The time response could be well described by two time constants, although it was difficult to determine their exact values due to limitations in the sampling rate of the sensor. The dominant time constant, accounting for approximately 88% of the response, was typically estimated as 2 msec or less; and the second time constant, accounting for the remaining 12%, was typically in the range of $300 - 500$ msec.

The spatial resolution of a sensor may be limited by coupling between the array elements and the spatial summation across an element. The spatial impulse response function for a single element was obtained by indenting the array sensor with a rounded 1.5 mm diameter probe to a constant depth at increments of 0.25 mm in the x and y directions (five trials at each position). The response data, along each axis, may be closely approximated by a gaussian (m.s.e. = 0.4%):

$$f_{spatial}(x) = \frac{A}{\sqrt{2\pi}\sigma} e^{-x^2/2\sigma^2} \tag{1}$$

where $A = 8.5$, $\sigma = 0.96$ mm and x corresponds to the distance from the center of the element. The proportion of the signal applied to a given element which is coupled into an adjacent element in the same row and column is less than 8% and in the diagonal directions is less than 1%.

The linearity of the spatial response was confirmed by the invariance of the inter-element coupling with load and successful superposition of two indentations applied to adjacent elements. Since the response is uniform and linear, the spatial impulse response can be used to deconvolve the signal, limited by noise. This can correct the measured pressures for spatial coupling between elements and spatial summation within an element, improving the accuracy of the measurements. Alternatively, if a model of the measured pressures is available, the predicted response can be convolved with the spatial impulse response (as in the following section) to account for spatial effects.

4 Verification of Sensor Response

As an independent verification of our sensor calibration, we verified the overall array sensor response by experimentally measuring the quasi-static pressure distribution generated by contact with a rubber ball (R_b = 31 mm, E_b = 540 kPa). For small, static displacements the response is expected to be linearly elastic and predicted by the Hertz theory of elastic contact for solids of revolution [Johnson, 1985]. This theory predicts the radial symmetric distributed pressure response, $p(r)$, as a function of indentation depth, δ, and radial distance from the center of contact, r:

$$p_{Hertz}(r) \quad = \quad \frac{2E^*}{\pi R}(R\delta - r^2)^{\frac{1}{2}} \tag{2}$$

where

$$\frac{1}{E^*} = \frac{1-\nu_b^2}{E_b} + \frac{1-\nu_a^2}{E_a}. \tag{3}$$

The modulus of elasticity of the array sensor, E_a, was 1 MPa, and both the ball and the array sensor were assumed incompressible ($\nu_b = \nu_a = 0.5$). The fraction $\frac{1}{R}$ is a constant describing the relative curvature of the two surfaces. Since, in our case, the array sensor is flat, the relative curvature is defined by the radius of the rubber ball.

Experimentally, the ball was mounted rigidly in a machinist's vise and a flat tipped, motorized indentor applied controlled indentations normal to the ball surface. A force sensor on the tip (maximum noise $\approx$ 0.1 N) measured the net force, and a magneto-resistive position sensor (maximum noise $\approx$ 0.02 mm) located on the motor shaft measured the indentation distance. The tactile array sensor described above was mounted in front of the force sensor and measured the pressure distribution.

The sensor was indented into the rubber ball at a rate of 0.2 mm/sec to emulate static conditions (four trials). Since the response was radially symmetric about the center of contact (as predicted by the theory), the pressure distribution is shown as a function of the radial distance from the center of contact (Figure 2). It is readily apparent from the data that the experimental response is qualitatively very similar to the parabolic shape characteristic of Hertz contact. However, it should also be noted that the data exhibits 'tails' towards the edges of contact which are not predicted by the theory. This is not unexpected given the spatial impulse response of the array sensor elements.

We fit the data to the predicted response, taking into account the spatial impulse response of an array sensor element:

$$p_{predicted}(r,\theta) = p_{Hertz}(r) * f_{spatial}(r,\theta) \quad (4)$$

where $p_{Hertz}(r)$ is defined in Equation 2 and $f_{spatial}(r, \theta)$ is the 2-D representation of Equation 1. The least squares error was minimized using a simplex search on R and E_b for all δ. The resulting fit had a m.s.e. of 5.5% with $R = 32.6$ mm and $E_b = 570$ kPa. The fit to the distributed response as well as to the net force response (m.s.e. = 3%) is shown in Figure 2. The actual response is very similar to the filtered Hertz contact model, including the presence of 'tails' towards the edges. In addition, the parameter values determined for R and E_b were within 6% of their actual values.

Unfortunately, there is no simple analytical solution to which we similarly can compare the dynamic response. However, to some extent, the accuracy of the dynamic response can be independently verified by comparing the sum of the pressure responses of the array elements to the force sensor measurements for various sinusoidal displacement inputs (e.g., Figure 3): for the range which we are interested in (0-2 N, $\leq$ 16 Hz), the mean squared difference is 3%.

5 Preliminary Biomechanical Measurements

Our main interest in developing and characterizing a distributed pressure sensor is to obtain quantitative dynamic measurements of the distributed mechanics of the fingerpad. As the fingerpad is typically an order of magnitude more compliant than the array sensor for our experiments [Pawluk and Howe], we will assume that the compliance of the sensor contributes negligibly to the response. Figure 3 shows preliminary results from indenting the fingerpad with a 8 Hz, 0.6 mm peak-to-peak sinusoidal displacement indentation superimposed on a 1.35 mm offset level. A more thorough characterization of the biomechanics of the fingerpad is underway.

6 Acknowledgments

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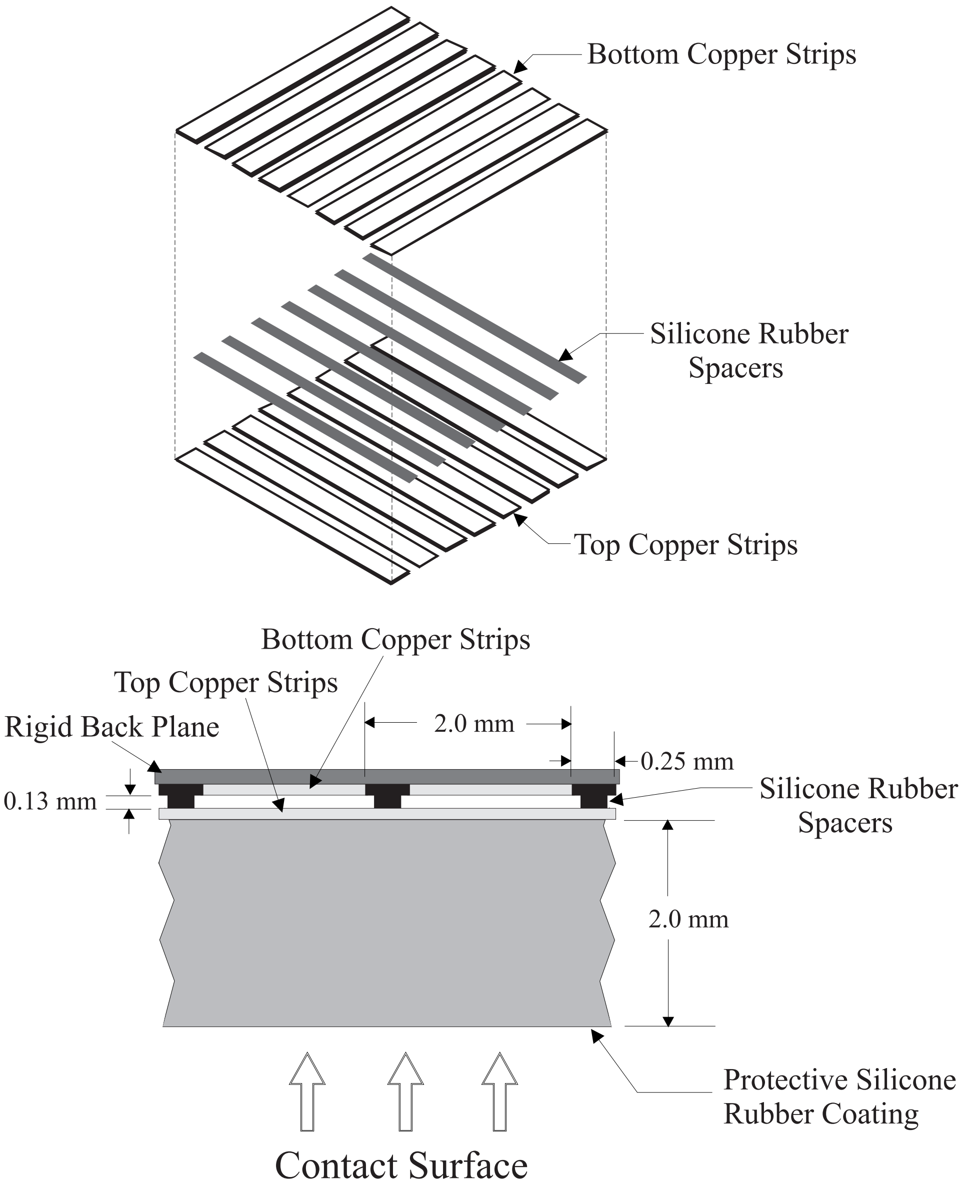

Figure 1: Tactile array sensor. Top: exploded view showing sensor construction. Bottom: side view showing the crossed layers of copper strips separated by silicone rubber spacers. A protective rubber coating is added on the contact surface.

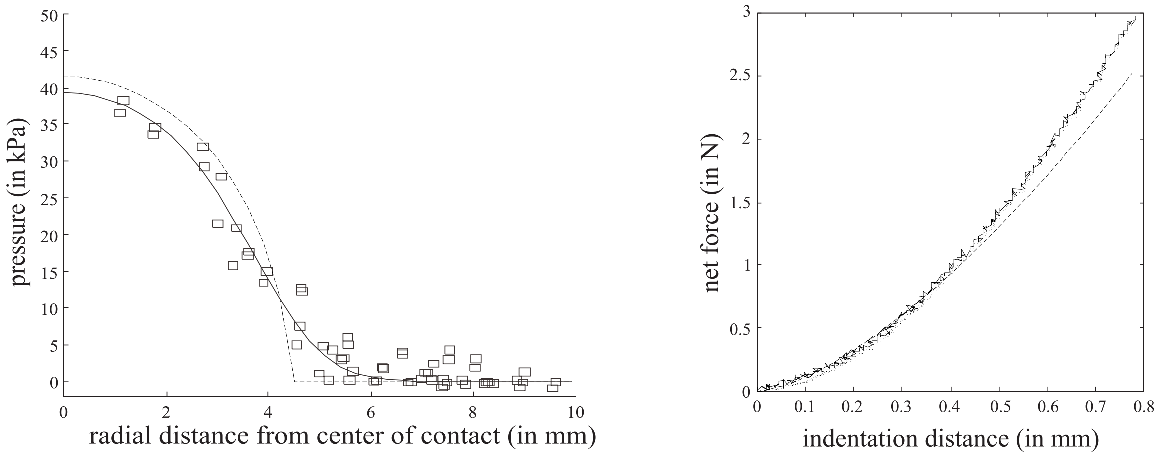

Figure 2: Quasi-static contact with a rubber ball (radius = 31.0 mm). Left: distributed pressure response at one indentation depth (0.59 mm, corresponding to a net force of 1.8 N); the size of the boxes indicates the error. The solid line shows the least squares fit of a Hertz contact function taking into account the spatial response of the array sensor. The dashed line shows the corresponding unfiltered Hertz contact response. Right: net force response. The solid and dotted lines compare the sum of the response of the pressure elements to the net force measured with the force sensor. The dashed line shows the response predicted by Hertz theory for the estimated parameters.

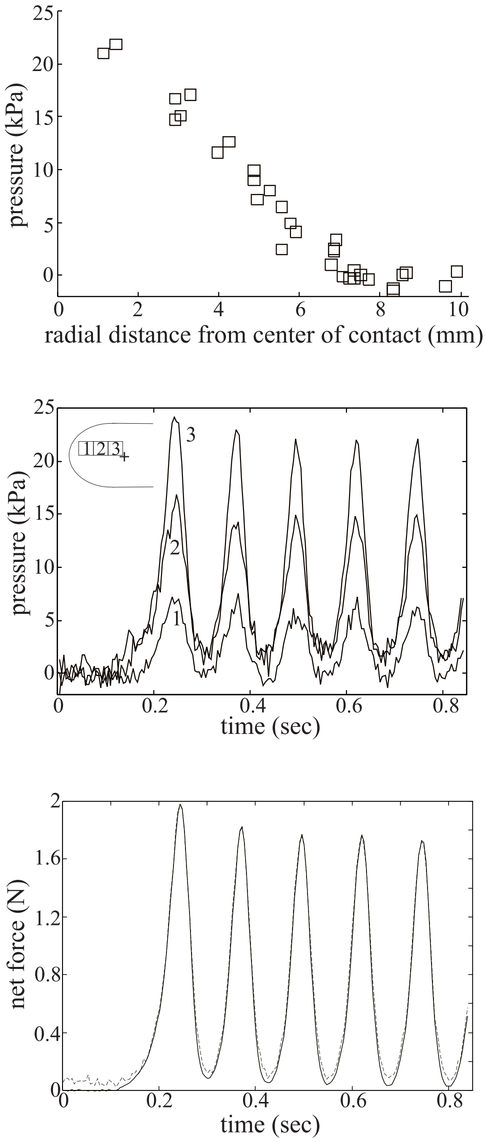

Figure 3: Dynamic contact with a human fingerpad. Pressure response measured for a 8 Hz sinusoidal displacement input. Top: distributed pressure response of the distal half of the fingerpad at one indentation depth (1.7 mm, corresponding to a net force of 1.9 N); the size of the boxes indicates the noise in the pressure measurements and the maximum alignment error in the position of the elements. Middle: time response for three individual tactile array elements along the line indicated in the insert. Responses decrease for elements further away from the center of contact (indicated by the cross). Bottom: net force response. The solid line is the force sensor measurement. The dashed line is the sum of the response of the pressure elements.