A Tactile Sensor for Localizing Transient Events in Manipulation

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Abstract

This paper presents a tactile sensor that provides transient event information at the finger-object interface. The multi-element stress rate sensor consists of piezoelectric polymer strips molded into the surface of the rubber "skin" covering the robot finger tip. These piezoelectric elements provide localized information important to manipulation control. We provide experimental results confirming the sensor's ability to detect three parameters. Contact events have been detected for signaling transitions between position and force control. Detecting local skin curvature provided information regarding contact shape and area. Finally, incipient slip, which is generated by small micro slips prior to gross slip, has been detected. By sensing all of these parameters, the utility of the multi-element stress rate sensor seems promising.

1. Introduction

The sense of touch is an important component of dexterous manipulation. Consider the inevitable clumsiness we experience when our sense of touch is diminished by wearing gloves. Physiological experiments show that when humans are deprived of tactile sensation with anesthetics, manipulation ability is seriously degraded even though musculature is unimpaired [Johansson and Westling 1984]. In robotics, experiments with multi-fingered robot hands demonstrate that without tactile feedback small unmodeled errors can accumulate, causing failure in complex manipulation tasks [Fearing 1987].

Many different parameters may be sensed through touch to enhance manipulation, including contact forces [Salisbury 1985, Bicchi 1989], pressure distributions [Fearing 1990, Maekawa et al 1992], and high frequency vibrations [Patterson and Neville 1986, Morrell 1990, Howe and Cutkosky 1989]. Vibrations are important indicators of *events* such as contact and slip. Detection of these events is particularly useful in complex tasks in unstructured environments. A simple example is the task of grasping and lifting a delicate object. Knowledge of the contact state is important for good control of this operation because before the fingers make contact with the object the positions of the fingers in space must be controlled, while contact forces must be considered afterwards. In an unstructured environment the exact location and shape of the object may not be known, so the instant of contact cannot be predicted. To avoid destabilizing or damaging the object it is therefore essential to detect the contact at the earliest possible moment so that the controller may respond appropriately.

Another important event that must be detected for skillful manipulation is slip, which permits optimal setting of the grasp force between the finger tips. If the grasp force is too low, the object will slip between the fingers; if it is too high, the object may be damaged. Humans show a remarkable ability to use a grasp force that is just slightly higher than the minimum to prevent slipping, even without a priori knowledge of object weight or frictional characteristics [Johansson and Westling 1984]. This ability is apparently based on sensing small vibrations that indicate the earliest stage of slip before gross sliding of the object has commenced. It appears that in the first fraction of a second after contact, signals from the tactile mechanoreceptors in the fingertips provide enough information to characterize the coefficient of friction of the object surface. This permits appropriate adjustment of the grasp force for a wide range of load forces.

Only a few studies have dealt with tactile event detection in robotic manipulation. The tactile sensor that has received the most attention in robotic research is the tactile array, which typically consists of individual pressure-sensitive elements arranged in a rectangular array over the contact surface of the finger tip. These sensors have only limited utility for event detection. Array sensors are usually multiplexed to reduce the number of wires between the transducer elements and the electronics. This impairs the ability to detect high frequency information. In addition, sensor elements are usually covered with a relatively thick layer of elastomer to reduce aliasing and improve durability [Fearing 1990], which also limits high frequency response.

Several sensors have been specifically designed to measure the vibrations that indicate incipient slip [Howe and Cutkosky 1989, Morrell 1990]. These sensors function by detecting the small vibrations that precede gross sliding. The mechanism responsible for these vibrations is not known, but is believed to be due to slip near the edges of the contact. For a curved finger tip the pressure is lower at the edge of the contact than at the center. When slip starts to occur, regions near the edges will give way and slide a short distance before the center starts to slip. This motion

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around the periphery appears in the form of vibrations, and since the center is still fixed, overall motion does not occur.

One high frequency sensor of particular interest in the context of this paper is the skin acceleration sensor developed by Howe and Cutkosky [1989]. This sensor consists of a miniature accelerometer bonded to the inner surface of the rubber skin covering a robot finger tip. Beneath the skin is a layer of foam rubber to provide compliance and help isolate the accelerometer from vibrations produced by the robot mechanism. The principal advantage of this sensor is that it intrinsically responds to changes in the quantity of interest, i.e., it measures the second derivative of the skin position. This avoids the noise that inevitably accompanies differentiation of a noisy sensor signal, and provides extremely high sensitivity to high frequency vibrations.

Because of this high frequency sensitivity the sensor has been successfully used to detect incipient slip and control grasp force in bench-top experiments. However, application to manipulation tasks with robot hands has proved difficult. This is because the sensor's sensitivity is not spatially localized. Vibrations appearing essentially anywhere in the finger tip are detected by the sensor, including vibrations from sources other than incipient slip such as skin movement and robot mechanism noise. Trembley and Cutkosky [1993] have addressed this problem and shown that by using two accelerometers at different locations on the skin some measure of disturbance rejection can be achieved. Unfortunately, the large active area of the sensor still poses fundamental limits to its use in slip detection. The ability to detect localized vibrations so that incipient slip at the periphery of the contact can be isolated from other sources of vibration is suggested.

For contact detection the skin acceleration sensor has other difficulties. When the finger approaches the object surface at relatively high speed, the rapid deceleration of the skin produces a large signal. However, at lower speeds the sensor response is diminished dramatically, making it difficult to detect contact. An additional problem is that the accelerometer will respond whenever the entire finger tip is accelerated, and differentiation of contact events from accelerations can be difficult.

To address these difficulties we have developed a new sensor for event detection in robotic manipulation. The sensor combines the spatial localization ability of array sensors with the high frequency derivative sensing advantages of the skin acceleration sensor. Small strips of a piezoelectric polymer are molded into the skin just beneath the surface. These transducers respond to stresses in the skin caused by contact forces and skin shape changes in their immediate vicinity. Signal processing electronics is configured to measure changes in stress, so the sensor is referred to as a "stress rate sensor." An earlier version of this sensor, using a single piezoelectric strip, was designed to measure extremely fine surface features down to a few microns in size by stroking the sensor over the object's surface [Howe and Cutkosky 1993]. However, this new sensor uses an array of piezoelectric strips and protruding "nibs" on the skin to localize manipulation events.

In this paper we investigate the use of the multi-element stress rate sensor to detect localized incipient slip, occurrence of contact, and local changes in skin curvature. First, we describe the sensor's design and characterize its basic performance. Next, we present experimental results demonstrating the ability to detect incipient slip and curvature localization. The sensor has also been used in manipulation experiments with a simple two-fingered robot hand, and we show that it is able to detect contact and incipient slip. Finally, we conclude with a discussion of these results and their implications for sensor design and control of dexterous manipulation.

2. Sensor design and characteristics

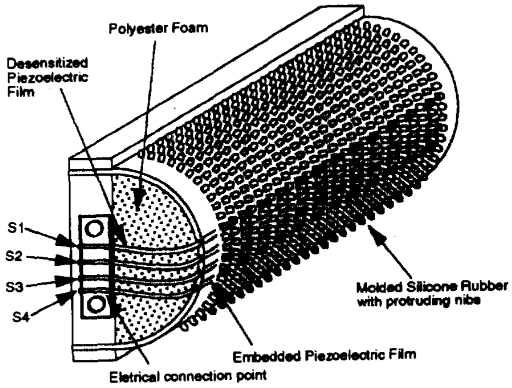

Figure 1. The multi-element stress rate sensor.

The prototype version of the multi-element stress rate sensor described here is part of a semi-cylindrical "finger tip" 25mm in diameter and about 45mm long (Figure 1). There are three primary components: strips of piezoelectric film, a silicone rubber skin with molded surface texture, and a foam core within the skin. Contact with objects in the environment occurs along the side of the cylinder. The skin is 0.8mm thick and a surface texture consisting of small protruding cylindrical "nibs" has been molded onto the surface. This pattern was selected to optimize the sensor performance after extensive testing, as described below. The skin is then wrapped around a semi-cylindrical polyester foam core and secured at the ends using a clamping mechanism.

2.1 Piezoelectric film strips

There are four 0.8mm wide piezo film strips molded into the contact surface of the skin at 3.2mm spacing. The strips run through the skin across the entire width of the finger tip and extend out from one edge of the skin for connecting to the signal processing electronics. To prevent response from flexing of the strips after they emerge from the skin this portion of the piezo film was desensitized by heating it to a temperature just above the Curie temperature. The piezo film is made of 0.028mm thick polled polyvinylidene fluoride (PVF2) film, a flexible polymer with very good piezoelectric response. The piezoelectric film acts as a capacitor on which charge is produced in proportion to the strain applied to the film. A thin layer of silver ink on the surface of the film collects the charge generated and provides electrical contacts for signal amplification and processing. The transduction constant between stress and charge is different in each direction within the film, but the sensitivities are large and similar in the directions of the thickness of the film and in one of the transverse directions. The thickness dimension of the film was oriented parallel to the skin surface, and the strips were cut such that the direction of sensitivity is oriented along the direction of expected slip.

The piezo film strips are connected to a FET-input op-amp configured as a current-to-voltage converter [Howe and Cutkosky 1993]. The piezo film generates a charge q proportional to the stress applied to the film σ. The current i at the input to the amplifier is the time derivative of q, so the output voltage v is proportional to the time rate of change of the stress, or to the stress rate:

$$v = \frac{dq}{dt} R_f \propto \frac{d\sigma}{dt} R_f$$

Here R_f is the feedback resistance and the op-amp effectively servos the voltage developed across the film to zero. Since the voltage across the film is minimized, inaccuracies due to charge leakage through the internal resistance of the film are negligible and the required amplifier impedance is far lower than for a conventional charge amplifier. Furthermore, the sensor has no DC response so it is immune to saturation due to drift and pyroelectric effects which are common problems with piezoelectric tactile array sensors [Buttazzo et al 1986]. The result is a transducer optimized for measuring changes in stress within the rubber skin.

2.2 Sensor response and skin texture

The key to this sensor's success in localizing events on the skin is the limited receptive area for each piezo film element. From solid mechanics we know that in the thin skin material the near-surface stress will be high in regions of high curvature [Fearing and Hollerbach 1985]. Furthermore, these stresses are far higher than the stress produced by the overall tension in the skin. Since the piezo film strips are located just beneath the surface of the skin, the predominant response is to changes in local curvature. This is in contrast to the situation for the skin acceleration sensor, where small displacements anywhere on the skin are readily detected by the sensor.

The texture on the outer surface of the skin (the pattern of small-scale shapes) is then extremely important for determining how local curvature changes when the skin is in contact with an object. A texture consisting of small protruding "nibs" is particularly effective. As the nibs make contact with an object surface they may be bent and even pushed over onto their sides. This generates large curvature changes and stresses at the base of the nib, and the piezo film elements respond very strongly. In defining the skin texture, numerous variations on nib size, shape, aspect ratio and spacing were tested. The size of the nibs and the surface roughness on which slip was occurring were correlated in such a way that larger nibs required a rougher surface to excite or pluck the nibs. However, changing from a flat ended nib to a hemispherical ended nib improved the detection of slip on smooth surfaces. This is probably the result of lower friction for Herzian contact interface in comparison to a larger flat contact interface. It also appears easier to pluck a cylindrical nib rather than a flat ended nib. Furthermore, longer nibs were more easily excited during slip, but shorter nibs produced a more localized signal. Since longer nibs were more difficult to mold, a relatively moderate 0.8mm length was chosen with a smaller 0.6mm diameter. A hexagonal close packed pattern with 0.8mm spacing served to minimize the tendency of grasped objects to "squirm" against the nibs.

2.3 Signal processing

Because of the derivative nature of this sensing modality, there is a great deal of high frequency information present in the signal. In experimental testing of the sensor we found that it was difficult to detect the slip signal with full bandwidth of the sensor (>10kHz). Thus, following current-to-voltage conversion the sensor signal is amplified and low-pass filtered. Surprisingly, the optimum 2 pole low pass filter 3dB frequency was found to be about 30Hz; this minimized noise while leaving the slip signal undiminished. Apparently the physical phenomenon associated with incipient slip has a large 10 to 30Hz component. The implications of this observation are further considered in the Discussion section below.

3. Sensor performance measurement

Two bench-top tests were performed using the test apparatus shown in Figure 2. The piezo sensor was mounted on the end of a two-axis force sensor and the force sensor in turn was mounted on a micrometer-driven translation stage oriented in the vertical direction. A linear bearing slide simulated the contact surface of a grasped object below the sensor. The slide was connected to a linear potentiometer for measuring its position. A weight suspended by a string across a pulley provided the shear force required to make the contact surface slip beneath the sensor. The forces at the finger tip, the position of the linear slide and the four elements of the stress rate sensor were measured at 3kHz using a 12 bit A/D converter in a laboratory computer.

The first test measured the sensor's ability to detect localized curvature changes. One cause of such change is the deformation of the finger tip skin as it is pressed against an object. Because the foam core of the sensor is highly compliant, a region of high curvature proceeds outwards from the center of the contact towards the periphery. For this test the finger tip was lowered smoothly on to the contact surface. The top trace corresponds to the piezo strip element furthest away from the center, and the third trace from the top is the piezo strip response of the center element, which makes contact first. The bottom trace is the measured normal force. As seen in Figure 3, the sensors respond in succession as the local curvature changes near each piezo element along with an increase in normal force. This demonstrates that the sensor does in fact respond to localized curvature, and that it can make an effective contact location sensor in addition to its event detection capabilities.

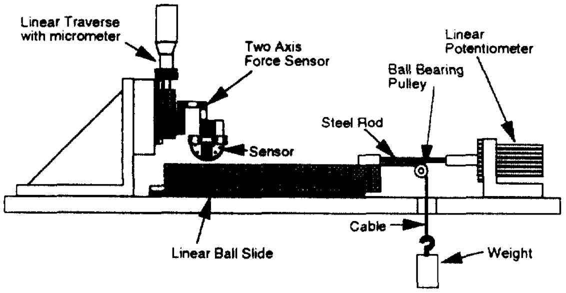

Figure 2. Bench top experimental apparatus for the piezoelectric skin sensor.

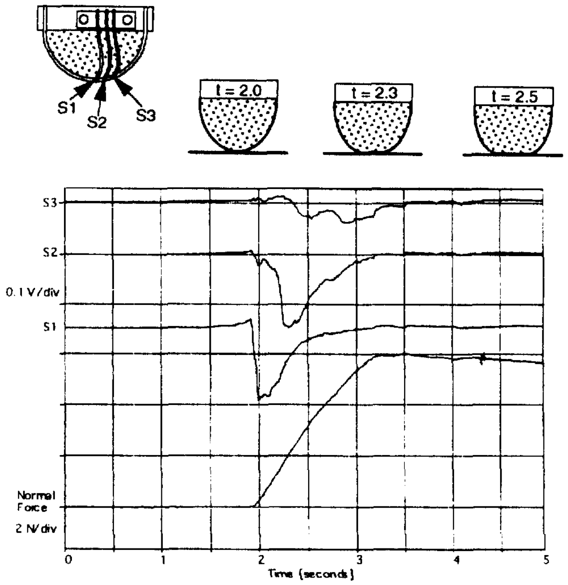

Figure 3. Response of the stress rate sensor elements to changes in local skin curvature.

For the incipient slip detection experiment the linear slide was moved to the left and the finger was lowered against it to prevent it from sliding. Then the finger was slowly raised to reduce the contact force until the linear slide began slipping under the force of the hanging weight. Initially, experiments were conducted with a hard rubber sensor over a hard material because of the larger signal amplitude. However, closer examination revealed that the normal force and the incipient slip signal always started to change together. As it turns out, the sensors were measuring the normal stress rate as the finger was being released from the surface. By using a compliant foam material, the normal force changes were isolated from the incipient slip signal as shown in Figure 4. The two sensor signals S3 and S4 are 95 and 47ms earlier than any measured motion. This "early warning" provides sufficient time for a robot hand controller to increase the grasp force and prevent the onset of gross slip. The other two sensing elements do not signal the impending slip because they are located away from the contact region. This spatial discrimination will permit the controller to robustly discriminate slip signals from other sources of vibration.

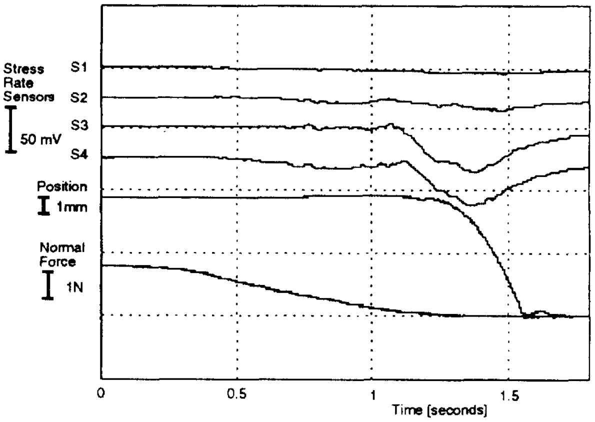

Figure 4. Detection of incipient slip. As the normal force is slowly decreased, the piezoelectric skin sensors show a slight response. The outputs from the third and fourth piezo elements change to indicate that slip is about to occur 95 ms and 47ms before gross slip respectively.

4. Manipulation experiments

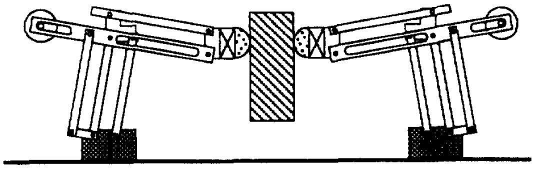

Figure 5. Planar direct drive two-fingered manipulator with the piezoelectric skin sensor mounted on the finger tips.

To demonstrate the usefulness of the sensors on a real manipulator, the stress rate sensor was mounted on one of the two-fingered planar robot hand shown in Figure 5. This manipulator has a direct drive, parallel link configuration for low friction and backlash and minimal moving mass. (For details of the manipulator design and performance, see Howe 1992.) Again, a two-axis force sensor near the tip of each finger measures the grasp and load forces. The stress rate sensor and the amplifying electronics were mounted directly on the finger.

First, the sensor's ability to detect contact events during manipulation were demonstrated in an autonomous robotic task. The manipulator was programmed such that the finger with the stress rate sensor approached the other finger at 2 cm/sec and touched the other finger until a threshold voltage of 15mV was detected. Using the other finger as the "object" provided independent verification of the contact force. After detection of contact, the fingers were retracted and reversed directions for another contact event.

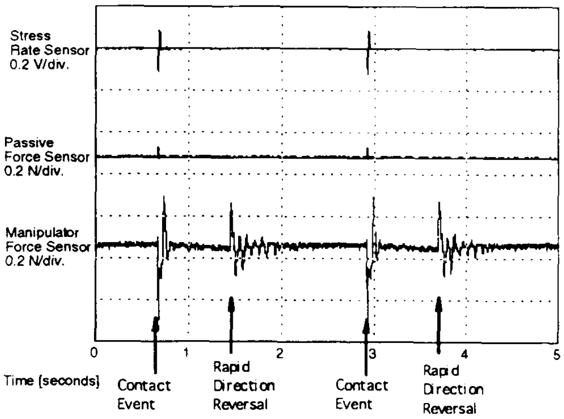

Figure 6. Detection of contact by thresholding the piezoelectric skin sensor signal. The finger tip mass together with the force sensor forms an accelerometer that responds to transmission vibrations and rapid accelerations.

The stress rate sensing elements were able to detect contact much better in comparison to the force sensor. The stress rate sensor is able to detect contact at a very low threshold value corresponding to approximately 0.05 Newtons. Also, as shown in Figure 6, the force sensor responds to both contact and rapid direction reversal. The mass of the finger tip acts as a proof mass thereby forming an accelerometer. However, the stress rate sensor is insensitive to changes in acceleration caused by the manipulator. Skin acceleration sensors were also sensitive to accelerations and vibrations from the manipulator.

Signals from incipient slip are much smaller than the signals from contact events, so detection of slip during autonomous manipulation is still an ongoing effort. However, signals from the sensors were recorded during teleoperated manipulation to show the current performance of the sensor for detection of slip. The planar manipulator system also includes a kinematically identical "master" manipulator that can be used to direct the "slave" hand described above. This experiment consisted of picking up an object from the table top, gradually decreasing the grasp force until the object began to slip followed by regrasping the object, then replacing it on the table. As shown by the force and the stress rate sensor signals in Figure 7, the sensor is able to detect the onset of contact, incipient slip, and release of the object. By measuring the force signals just prior to slip, the friction coefficient between the sensor and the manipulated object can be determined and the appropriate grasp force calculated [Bicchi et al 1989].

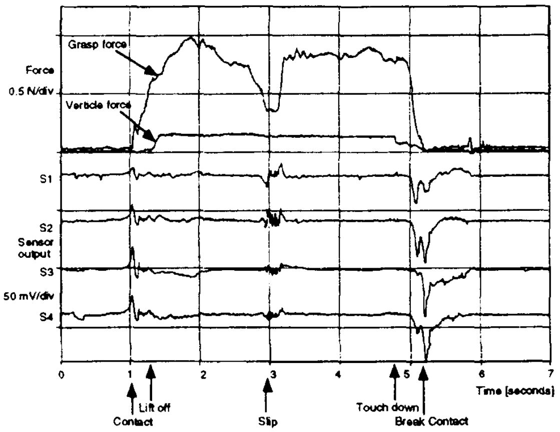

Figure 7. Force and piezoelectric skin sensor signals recorded during teleoperation. The task involved grasping and lifting an object, decreasing the grasp force to induce slip, regrasping and replacing the object.

5. Discussion

The multi-element stress rate sensor fills a gap between tactile array sensors and skin acceleration sensors. Tactile array sensors provide a highly localized but low frequency stress information. On the other hand, skin acceleration sensors are obviously sensitive to high frequency information but have poor spatial localization ability. The experiments presented here demonstrate that the stress rate sensor bridges these capabilities by providing spatially resolved vibratory information. In terms of frequency ranges, array sensors seem best for DC to 10Hz information, the stress rate sensor for 10-50Hz, and the skin acceleration sensor for 50-1000Hz. In terms of tasks, array sensors seem most useful for low frequency shape information such as controlling the rolling of fingers over curved object surfaces [Fearing 1987, Maekawa 1992]. The skin acceleration sensor is perhaps most useful for the smallest transient information, such as remote vibrations in grasped objects and tools generated when an object is set down on a table top. As demonstrated above, the stress rate sensor is well suited to detecting the earliest stages of contact and slip, and spatial location of curvature changes propagating across the finger tip.

One interesting aspect of this work is that human mechanoreceptors seem to evidence much the same "division of labor" between sensors. There are four types of specialized mechanoreceptor nerve endings in human finger tip skin [Johansson and Vallbo 1983]. Two of these sensors respond to static and slowly changing stimulus, and are believed to be responsible for sensing force and fine-scale pressure and shape information. These are perhaps analogous to the finger tip force and tactile array sensors. Another mechanoreceptor, the FAII nerve endings, responds to vibratory stimulus in the 50-500Hz range. The variation in response with frequency for these receptors suggests that they are sensitive to acceleration. These sensors have large receptive areas (as large as an entire finger surface in some cases), so they are clearly analogous to the robotic skin acceleration sensor. Finally, the FAI nerve endings respond to changing skin shape from roughly 5-60Hz, and show the spatial selectivity that the stress rate sensor also possesses.

Another question that arises from these experiments is, "How are humans able to detect the coefficient of friction during the initial grasp stage of manipulation when the skin is being deformed due to the increase in grasp force?" It has been suggested that detection of localized slip occurs at the edges of contact area, but this is where the skin curvature is changing most rapidly. It could be possible that incipient slip is detected in the center of contact where skin curvature is not changing. Another hypothesis is that slip information is somehow differentiated through elaborate processing by highly trained neural networks within the central nervous system.

6. Conclusions and Future work

The multi-element stress rate sensor presented here has been used to detect three important parameters in manipulation. The detection of contact is important for adapting to the environment and changing the controller between position and force control. Local skin curvature information can be used to ascertain contact shape and size. Finally, detection of incipient slip, generated by small micro slips prior to gross slip, has been demonstrated. Currently, work is in progress to implement autonomous slip detection and grasp force control. Further work is planned on integration of stress rate, skin acceleration, and tactile array sensors into a single finger tip, which will be used to further delineate the appropriate roles of tactile sensors in various manipulation tasks. The goal is to deduce the principles that will permit truly dexterous autonomous robotic manipulation.

Acknowledgments

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References

A. Bicchi, J. K. Salisbury, and P. Dario. Augmentation of grasp robustness using intrinsic tactile sensing. In *Proceedings of IEEE International Conference on Robotics and Automation*, pages 302-307, Scottsdale, Arizona, May 1989

G. Buttazzo, P. Dario, and R. Bajcsy. Finger based explorations. In David Casasent, editor, *Intelligent Robots and Computer Vision: Fifth in a Series, Proceedings of SPIE* , Volume 726. pages 338-345, Cambridge, MA, October 28-31, 1986.

R. S. Fearing and J. M. Hollerbach. Basic solid mechanics for tactile sensing. *International Journal of Robotics Research*, 4(3):40-54, Fall 1985.

R. S. Fearing. Some experiments with tactile sensing during grasping. In *Proceedings of the 1987 IEEE International Conference on Robotics and Automation*, pages 1637-1643, Raleigh, NC, March 31-April 3, 1987.

R. S. Fearing. Tactile sensing mechanisms. *International Journal of Robotics Research*, 9(3):3-23, June 1990.

R. D. Howe and M. R. Cutkosky. Sensing skin acceleration for texture and slip perception. In *Proceedings of the 1989 IEEE International Conference on Robotics and Automation*, Scottsdale, AZ, May 1989.

R. D. Howe. A force-reflecting teleoperated hand system for the study of tactile sensing in precision manipulation. *IEEE Conference on Robotics and Automation*, Nice, France, pages 1321-1326, May 1992.

R. D. Howe and Mark R. Cutkosky. Dynamic tactile sensing: Perception of fine surface features with stress rate sensing. *IEEE Transaction on Robotics and Automation*, June 1993

R. S. Johansson and G. Westling. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, 56:550-564, 1984.

R. S. Johansson and A. B. Vallbo. "Tactile sensory coding in the glabrous skin of the human hand," *Trends in NeuroSciences*, Vol. 6, No. 1, pages 27-32, 1983.

H. Maekawa, K. Komoriya, and K. Tanie. Manipulation of an unknown object by multifingered hands with rolling contact using tactile feedback. In *Proceedings of the 1992 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS '92*. Raleigh, North Carolina, July 7-10, pages 1877-1882, 1992.

J. B. Morrell. *Force modulation of a robot gripper using slip detection.* Master's thesis, University of Washington, June 1990.

R. W. Patterson and G. E. Nevill, Jr. The induced vibration touch sensor - a new dynamic touch sensing concept. *Robotica*, 4:27-31, 1986.

J. K. Salisbury. Interpretation of contact geometries from force measurements. In M. Brady and R. P. Paul, editors, *Robotics Research: The First International Symposium.* MIT Press, 1984. Also reprinted in Salisbury 1985.

M. Trembley and Cutkosky. Estimating Friction Using Incipient Slip Sensing During Manipulation Tasks. *Proceedings of the 1993 IEEE International Conference on Robotics and Automation*, Atlanta, GA, May 1993.