Sensing Skin Acceleration for Slip and Texture Perception

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Abstract

We present a scheme for sensing small accelerations of the outer "skin" covering the fingers of a manipulator. Humans use a similar sensory capability to provide information for many purposes, including differentiating fine surface textures and detecting the incipient slip of a grasped object. Our sensor is constructed with a thin rubber skin covering a soft inner layer of foam rubber. This decouples the skin from the manipulator structure, isolating it from structural vibrations and facilitating the tracking of object surfaces. An accelerometer attached to the inner surface of the skin measures the large local accelerations produced when areas of the skin catch and snap back as the sensor moves against a surface. We present experimental confirmation of the ability to detect the onset of slip, and discuss the sensor response to various surface texture parameters.

1 Introduction

Current tactile sensing research has emphasized finding object shape and contact forces [*e.g.* Dario 1985, Fearing 1988, Allen 1987]. However, there are other important functions of tactile sensing: for example, learning about surface texture and frictional properties is important for both manipulation and object recognition. Our research indicates that sensing small accelerations of finger skin provides information that is very useful for such tasks. In addition, skin acceleration provides information about slip, which is crucial to successful manipulation.

We begin by reviewing pertinent physiological knowledge about human tactile sensing, which shows that there are specialized, sensitive acceleration sensors in our fingertip skin. Experimental evidence shows that such cutaneous sensors provide vital information about slip at the contact between finger and object. Studies on texture sensing suggest that information from each of the several types of mechanical sensors in the fingertip skin, including acceleration sensors, are compared in assessing texture.

We then describe the construction of a simple sensor for skin accelerations. Tests of basic sensor performance confirm the expected high sensitivity and large receptive field size. We have found that the sensor is capable of detecting the earliest stages of slip between the sensor and a test surface, and we present experimental confirmation of this ability. We also consider factors influencing the ability to differentiate fine surface textures and the performance of this sensor. Finally, we describe the relation of this work to our Stress-Rate sensing scheme (Cutkosky and Howe 1988) which provides complimentary information also obtained in a dynamic manner.

2 Human Sensing of Skin Acceleration

People can detect displacements of fingertip skin as small as 1 or 2 microns, but only if the displacement changes quickly as a function of time (Verrillo 1971). This ability to sense such tiny motion is possible because we sense accelerations. If the applied displacement varies sinusoidally with time as $x(t) = asin(\omega t)$, then the resulting acceleration is $\frac{d^2x(t)}{dt^2} = -a\omega^2 sin(\omega t)$. Thus the acceleration is proportional to the frequency ω squared. The smallest human detection threshold of 1 micron at 250 Hz thus corresponds to an acceleration of about 2.5 m/s^2. This is about 1/4 the acceleration of gravity, a physical quantity far easier to detect than a single micron of displacement.

Further evidence that humans in fact sense accelerations is provided by the -12dB/octave slope of the perception threshold curve from 50 to 250 Hz (Figure 1). This is precisely the slope corresponding to a fixed minimum detectable acceleration throughout this frequency range, so the amplitude which produces that acceleration varies inversely as the second power of frequency. This also indicates that the minimum acceleration threshold is approximately 2.5 m/s^2 throughout the range of 50 to 250 Hz.

It is interesting to note that the Pacinian corpuscles which are believed responsible for acceleration sensing have large re-

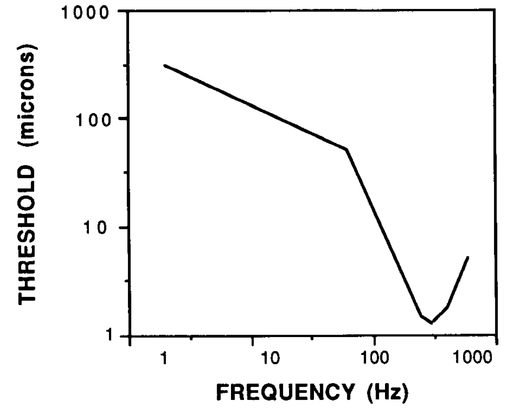

Figure 1: Human tactile sensing thresholds. (Adapted from Verrillo 1971)

ceptive fields (diameter $\gg$ 1 cm) with poorly defined edges (Johansson and Valbo 1983). The information they provide is thus poorly localized in space. This means that acceleration information is non-spatial: it provides temporal, intensity, or modal information, rather than the location of specific events on the skin. People are capable of making excellent use of such non-spatial information. Early experiments [Katz 1925, Krueger 1970] showed that people could identify textures through vibration alone, without the benefit of a distributed array of sensors. Katz's experiments, in which people dragged nails, pencils or sticks over cloth, wood and other materials while holding the implements in their hands or even clamped between their teeth, showed that people still reached quite accurate assessments of the material being "touched," without the benefit of distributed finger contact.

2.1 Texture sensing

People make use of the ability to sense small, fast displacements in a number of ways; two of the most interesting are in texture perception and slip detection. Texture here refers to distributed small-scale surface properties; generally features larger than about 1 mm are perceived as separate forms, while smaller features are perceived as texture (Johansson and Valbo 1983). Fine form perception works without hand motion, while sensing texture requires that the fingers move over the surface.

Our ability to resolve two pointed indentations on our fingers is limited to spacings greater than about 1 mm, and this is also approximately the distance between the centers of the receptive fields for the most closely spaced types of mechanoreceptors. Thus our ability to distinguish fine textures is remarkable in that it succeeds in differentiating between surface properties that differ only on a scale at least an order of magnitude smaller than the presumable resolution limit of the individual sensors.

Johnson (1983) suggests that texture is sensed as the relative excitation of three different types of receptors in the fingertip skin. Each of these sensors responds to a different mode of mechanical excitation, and each has a different frequency response characteristic. From these results it appears that our experience of texture is built from combinations of slow curvature measurements, dynamic skin stretch measurements, and spatially unresolved acceleration measurements. Thus texture sensing is an example of using modal and intensity information as well as spatial information.

2.2 Slip sensing

Slip detection plays a vital role in our ability to successfully grasp and manipulate objects. Johansson and Westling (1984) have elucidated the mechanisms involved by monitoring the grasp force and object acceleration as people lifted small objects. Most people use a grip force just greater than the minimum required for lifting the object, thus minimizing effort and avoiding object damage. After a disturbance or when an incorrect estimate of the minimum grip force was made, the object began to slip from the hand. These occasional small accelerations of the object were quickly followed (< 100 msec) by an increase in the grasp force, before the object moved a significant amount with respect to the hand. Interestingly, these rapid corrections to the grasp force occurred automatically and unconsciously. By anesthetizing the surface of the fingertip skin Johansson and Westling show that these corrections to the grasp force are prompted by information from cutaneous tactile sensors. Presumably these sensors detect that the skin in a small region of the contact has slipped and displaced slightly. This ability to detect minute, fast skin displacements suggests that accelerations may in fact be the physical quantity sensed.

3 Sensor Construction

We have constructed a simple prototype sensor to investigate skin acceleration sensing. Because it is designed to slide smoothly over surfaces during exploration and to be used as a gripping member for manipulation, the compliance of the sensor is of great importance. If the sensor surface is stiff (*e.g.* made from hard rubber), then small changes in the height of the sensor above the test surface will result in large changes in the contact force. These changes in force will make it difficult to accurately track the surface and prevent the outer skin of the sensor from flexing and recoiling as it passes over surface features. A stiff sensor will also couple vibrations in the supporting structure to the sensing element.

On the other hand, a thick, soft surface on the sensor will envelope small surface features on a grasped object, providing large contact areas and improving grasp stability. However, a

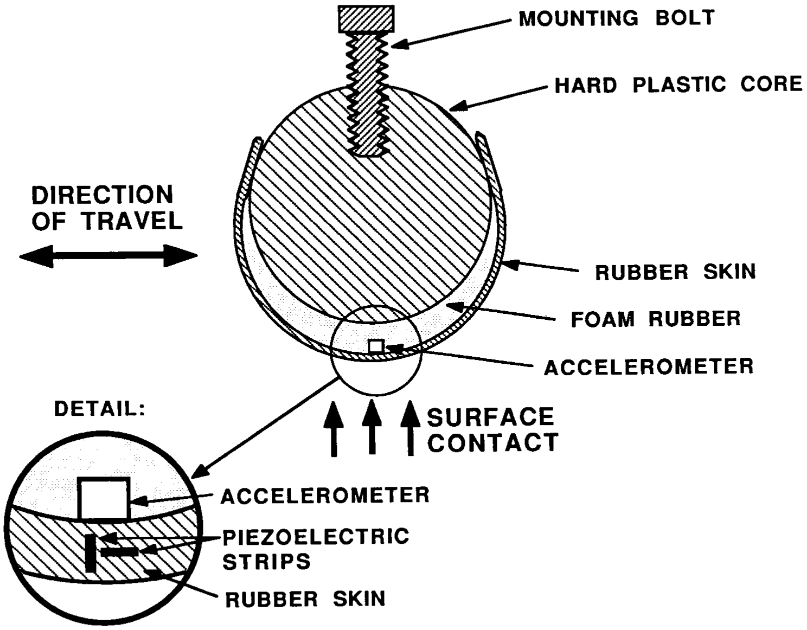

Figure 2. Cross section of skin acceleration sensor. Detail shows the accelerometer mounted on top of the rubber skin containing piezoelectric strips used in the Stress-Rate sensing scheme (see section 4.3).

soft outer skin will be fragile and easily damaged. Our approach is thus to construct the sensor with a thin outer skin of relatively dense rubber and a thick inner layer of soft foam rubber, all surrounding a hard plastic core. Besides increasing durability, the use of a hard skin increases local stresses in the surface of the sensor, which enhances the performance of the Stress-Rate sensing scheme described in section 4.3 below.

A cross section of the sensor is shown in Figure 2. The core of sensor is a hard plastic cylinder 25 mm in diameter and 50 mm long. A mounting bolt attaches the sensor to the supporting structure so that the axis of the cylinder is parallel to the test surface and perpendicular to the direction of travel during sliding. Around this core is a layer of soft polyurethane foam with an uncompressed thickness of about 20 mm. A relatively stiff outer skin of textured silicone rubber 1 mm thick is wrapped around the foam, partially compressing it, so that the final thickness of the foam is about 10 mm. Before attachment, a small accelerometer is mounted to the inner surface of the skin using a silicone rubber adhesive. The accelerometer is a conventional quartz crystal instrumentation-quality device with a specified noise level of 0.1 m/s^2. It measures 5 mm in diameter and 6 mm high and weighs 0.5 g.

Another important consideration is the texture on the surface of the rubber skin. A very smooth skin (surface roughness less than about one micron) produces a very large coefficient of friction, which causes large scale stick-slip motion as the sensor slides over smooth surfaces. This makes control of sliding or manipulation difficult and overloads the acceleration sensor, so this skin texture is to be avoided.

A better texture consists of parallel ridges a few hundred microns wide and up to a few hundred microns high, reminiscent of human fingerprints. This skin texture avoids the adhesive behavior of very smooth skin, and permits the sensor as a whole to slide smoothly. However, individual ridges seem to catch and snap back as the sensor moves against a surface, producing large local accelerations of the skin which are easily detected by the sensor. In contrast, a mat finish on smooth skin (roughness of a few tens of microns) slides smoothly, but provides only

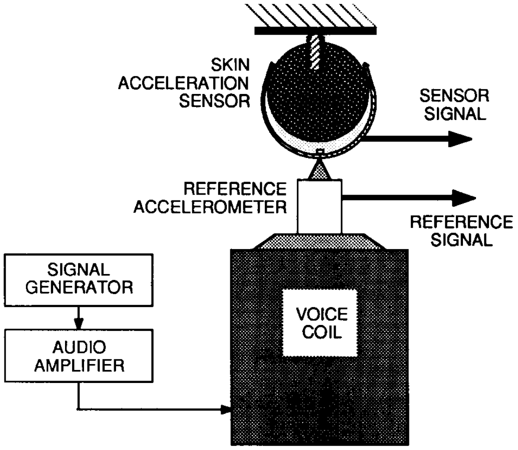

Figure 3: Setup for measuring basic sensor performance.

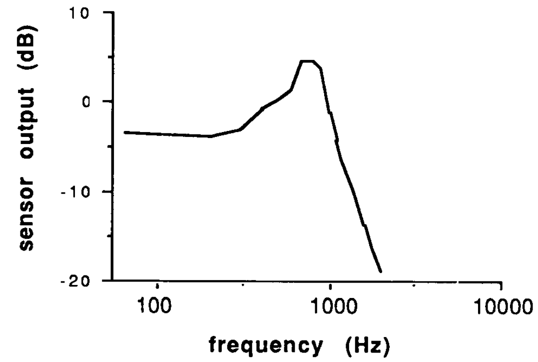

Figure 4: Sensor frequency response using setup of preceding figure.

minimal excitation of the acceleration sensor. Lederman (1978) has suggested that catch-snap back of human finger print ridges contributes to human tactile sensitivity in much the same way.

3.1 Performance tests

The basic performance of the sensor was ascertained by measuring the sensor response to vibrations of known amplitude and frequency applied to the sensor surface. This test signal was generated by a voice coil (solenoid) driven by an audio amplifier and signal generator and was monitored with a reference accelerometer mounted on the moving coil (see Figure 3). The frequency response is plotted in Figure 4. The response is flat until the vicinity of 700 Hz, where a low-Q resonance briefly raises the response about 10 dB before rolling off at about 18 dB/octave. This resonance is probably due to the mass-spring system formed by the accelerometer and the rubber skin just below it. Effects of this resonance are discussed in section 4.2 below.

4 Experimental Results and Discussion

4.1 Slip detection

Slip detection has been the subject of considerable interest in robotic research because of its importance for successful grasping. Early approaches used a stylus or rolling ball in the gripping surface to detect motion of the grasped object. More recent studies have attempted to monitor small displacements of the gripper surface (Rebman and Kallhammer 1986) or acoustic emissions (*e.g.* Dornfeld 1987). None of these approaches have proved to be a general solution to the slip sensing problem.

We have found that sensing skin acceleration is an effective and reliable method of detecting incipient slip. To test the skin acceleration sensor's ability to detect the onset of slip we used a simple apparatus for inducing and monitoring sliding (Figure 5). The skin acceleration sensor was held fixed against the top surface of a platform that was free to slide horizontally on low friction bearings. The normal and shear forces between the sensor and platform were controlled with weights and the location of the platform was monitored with an LVDT position sensor.

Several loading procedures were used. For example, weights were slowly added until the shear force overcame the frictional force between sensor and platform; or the platform was restrained by a catch while the shear force was increased beyond the friction limit, then the catch was released. In all cases, the position of the platform and the sensor output were simultaneously recorded with a computer and A-to-D converter.

Figure 6 shows the results from a typical run. The platform accelerates from rest, so even if the platform acceleration is large the displacement changes very slowly at first. However, output from the sensor commences with the first minute displacements. We believe that catch-snap back of the skin ridges produces brief and localized but intense bursts of skin acceleration, which the sensor is able to detect. In most cases, significant sensor output begins 40-100 msec *before* the platform has moved 1 mm. This interval is easily sufficient for a controller to increase the grasping force or take some other corrective action before a grasped object

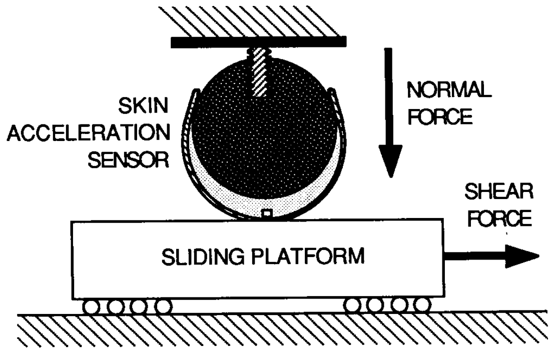

Figure 5: Apparatus for testing skin acceleration sensor's ability to detect incipient slip.

has moved significantly, just as in the human case.

4.2 Texture perception

Previous robotic research on texture perception has included several specialized sensors, such as a piezoelectric "fingernail" designed to be dragged over textured surfaces (Buttazzo, Dario and Bajcsy 1986). Studies of texture interpretation usually analyze data obtained with pressure array sensors (e.g. Ellis 1986).

To explore the skin acceleration sensor's ability to sense textures, we have experimented with dragging the sensor over various surfaces at a range of speeds and normal forces. The signal varied in amplitude only slightly with normal force, somewhat more with surface roughness and a great deal with speed. But the frequency content was almost always centered on the same approximately 700 Hz resonant frequency we found in the frequency response test described in section 3.1.

The variation with speed was a "threshold effect:" below a critical speed, the output was small, while above that speed, the signal became large very quickly. This can be seen in Figure 6, where the signal increases dramatically as the platform picks up speed. The critical speed for sliding on paper was about 50 mm/sec, although there was substantial and unpredictable variation in this speed. The frequency of the signal was very strongly peaked around 700 Hz, suggesting that once the sensor attains sufficient speed the resonant mode becomes excited.

Is the fact that the sensor output is predominantly at the resonant frequency peculiar to this particular sensor design (and its relatively large and massive accelerometer), or is this sensing technique always going to show such resonances? Lederman (1978) suggests that the frequency in human tactile sensing is often determined by the mechanics of the finger ridges, not the surface. This implies that resonances may be inescapable or that they may even be desirable, since at the resonance frequency the system will produce a large output signal for small input energy.

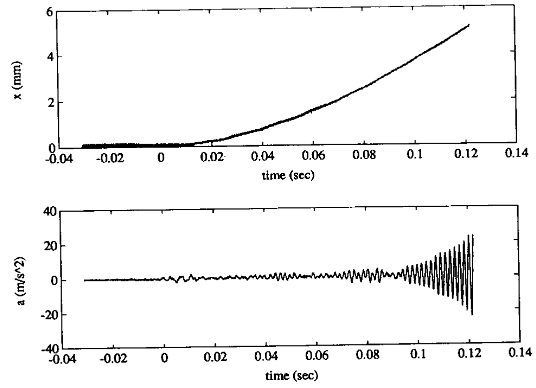

Figure 6: Typical data for slip detection. Upper trace: position of the platform. Lower trace: sensor output. The platform surface was covered with photocopy paper. Time axis zero refers to the instant when sensor output first exceeds 1.0 m/s^2.

Another pertinent factor is that this sensor responds almost exclusively to vertical acceleration; there may be other interesting phenomena in the horizontal directions. In particular, the resonance we observe is probably due to the accelerometer mass and the skin beneath it acting as a as mass-spring system, oscillating in the vertical direction. A resonance in the horizontal direction might be strongly excited by skin ridge catch-snap back; this would be closer to the mechanism suggested for humans.

4.3 Stress-Rate sensor

The skin acceleration sensing technique described here can be used synergistically with the Stress-Rate sensing technique that we have also been developing (Cutkosky and Howe 1988). This approach gathers spatial information about surface features and texture as the sensor moves over a surface. Thus although these techniques provide complimentary information, both are readily implemented in a single sensor.

The basic principle of the Stress-Rate sensor is to measure the rate of change of the stresses induced near the surface of the sensor skin as it slides over surface irregularities. This is accomplished by embedding small strips of the piezoelectric polymer PVF2 just below the skin surface (see detail in Figure 2). Because stress produces charge in the piezo film strips, changes in stress produce an electrical current which can be easily amplified and measured. Thus the output from this sensor is proportional to the stress rate at the piezo film strips. Signals are quite large, although extracting geometrical information is somewhat complicated due to noise generated by the sliding process.

Since this sensor is also designed for sliding and is sensitive to vibrations, it has the same requirements as the skin acceleration sensor for a compliant surface to provide smooth tracking and isolation from the supporting structure. Because it senses the stresses induced in the skin by surface features, the Stress-Rate sensor benefits by having a hard skin on the outside which enhances the local stress concentrations near the surface. Thus to combine Stress-Rate sensing with the skin acceleration sensor described here, we use piezo film strips molded into the rubber skin just above the contact area and just below the accelerometer (Figure 2).

4.4 Improvements to the sensor design

The sensor we have described here represents a first attempt at building such a device, and many improvements are already apparent. We plan to use a smaller and more sensitive accelerometer, which would permit us to reduce the sensor receptive field size and increase the resonance frequency. We also plan to experiment with sensing accelerations in the horizontal directions.

The compliant layer beneath the skin could be filled with a fluid instead of foam, which would result in greater uniformity of pressure distribution. Damping could be controlled by choosing the appropriate fluid viscosity. The stiffness and texture of the outer rubber skin could also be optimized in a number of ways.

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