A Robust Micro-Vibration Sensor for Biomimetic Fingertips

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***Abstract*—Controlling grip force in a prosthetic or robotic hand requires detailed sensory feedback information about microslips between the artificial fingertips and the object. In the biological hand this is accomplished with neural transducers capable of measuring micro-vibrations in the skin due to sliding friction. For prosthetic tactile sensors, emulating these biological transducers is a difficult challenge due to the fragility associated with highly sensitive devices. Incorporating a pressure sensor into a fluid-filled fingertip provides a novel solution to this problem by effectively creating a device similar to a hydrophone, capable of recording vibrations from lateral movements. The fluid conducts these acoustic signals well and with little attenuation, permitting the pressure sensing elements to be located in a protected region inside the core of the sensor and removing them from harm's way. Preliminary studies demonstrate that high frequency vibrations (50-400Hz) can be readily detected when such a fingertip slides across a ridged surface.**

I. Introduction

FINE control of grip force for the human hand is made possible largely by the wealth of tactile sensory information delivered to the central nervous system [1]. When making a precision pinch between two fingers, the muscles in the human hand deliver just enough grip force so that an object does not slip out of grasp [2]. This desirable behavior requires finely tuned sensory neurons capable of detecting microslips between the skin and the object when the ratio of gripping to lateral forces at the fingertip approaches a critical threshold [3]. In the biological hand, Pacinian corpuscles with frequency responses of 60-500Hz [4] are capable of measuring these vibrations associated with slip that can be as small as a micrometer around their center frequency of 200Hz [5]. These neural signals delivered by these sensory cells also contain a rich array of information for detecting fine texture during exploratory movements [6].

An advanced mechatronic hand or robotic manipulator will need artificial sensors to replicate the sensing function of the human finger. This has previously been divided into two categories of events to be sensed: those associated with static forces (normal and tangential to the surface) and those associated with the dynamics of sliding across a surface. For a comprehensive review of existing robotic tactile sensing technologies see [7][8][9]. This paper investigates robust sensing strategies for dynamic tactile sensing.

Pruski and Mutel [10] suggested that is might be possible to extract slip information from noise in a resistive sensor of normal force but did not present data on sensitivity or frequency response. Howe and Cutkowsky [11] took a more direct approach to sensing vibration in compliant skin by attaching an accelerometer but this involved mounting a fragile MEMS device where it would be prone to damage. Similarly, Dario et al. [12] mounted a piezoelectric polymer (polyvinylidene fluoride) near the skin surface, where it would be difficult to protect such a high impedance device from ambient moisture. Other variations using these piezoelectric materials have been investigated as dynamic sensors [13][14][15], however using fragile elements near contact surfaces reduces the robustness of these sensors.

While these sensors work fine for specific applications in controlled laboratory environments, they all share the common trait of requiring fragile sensing mechanisms to reside near the contact surface of the sensor. Biological hands are afforded with the ability to regenerate damaged skin and receptors, but an alternative approach for engineered systems is to keep delicate sensing devices a safe distance from possible damage, while still retaining as much sensitivity as possible. In this paper we propose a novel class of tactile sensors capable of measuring the microvibrations associated with slip at a remote location that is protected from potential damage from the harmful environments our hands encounter on a daily basis. By taking advantage of the excellent propagation of sound waves through an incompressible fluid, we have overcome the supposition that transduction must be done near the surface of a tactile sensor [9].

II. Methods

A. Designing a Robust Micro-Vibration Sensor

Our design challenge was to develop an easily repaired, highly durable, yet sensitive and precise tactile sensing device that contains a replaceable compliant skin with no sensing elements or electronic connections. Instead all sensing mechanisms would remain on or in a rigid core to which the skin can be attached. In previous work, we have developed a biomimetic tactile array that measures the distribution of applied forces by detecting deformation of a fluid-filled space that functions mechanically like the finger pulp (Fig. 1) [16]. Sensing electrodes distributed over the

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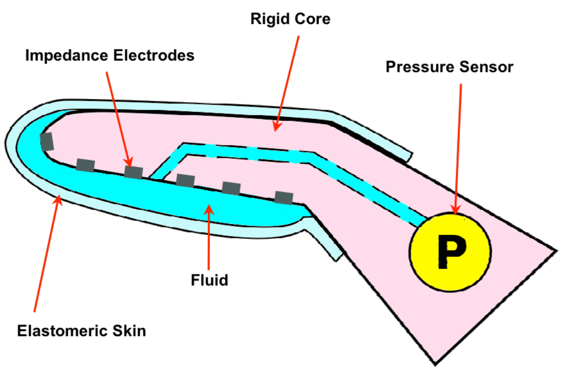

Fig. 1. Tactile sensor design. Prototype for micro-vibration sensor is comprised of a rigid core surrounded by a deformable fluid contained within an elastomeric skin. A pressure sensor is housed away from the contact area protecting it from damage. This is a critical design feature as many alternative approaches require delicate sensors to be placed on or near the skin's surface. As the sensor slides across a textured surface micro-vibrations generated from sliding friction are transduced into fluid pressure vibrations .

surface of the core detect these deformations by changes in the AC impedance with respect to reference electrodes. However, the fine micro-vibrations due to sliding contact do not produce enough fluid deformation to detect micro-slips with a similar impedance-based approach. This paper describes the incorporation of an off-the-shelf pressure transducer to detect vibrations in the fluid associated with texture and slip.

The incompressible, low-viscosity fluid is an efficient conductor of acoustic frequency vibrations (Fig. 2). Given the long wavelengths of the relevant frequencies (λ = 3m @ 500Hz), it was possible to locate the sensitive MEMS transducer and its supporting electronics away from the skin and within the protective core of the sensor.

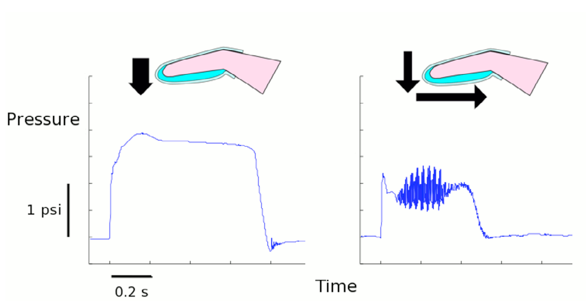

Fig. 2. Sensing of sliding micro-vibrations (right) compared with no-slip control (left). In the no-slip control case, the sensor was manually pressed down on a rigid surface (tabletop) and released after some time showing an increase in fluid pressure during this task. In the sliding case, the sensor was pressed down on the same surface and slid across while maintaining a constant downward force. High frequency spectral energy was readily observed in this task and has been attributed to micro-vibrations generated from sliding.

B. Fabrication, Inflation, and Leak Detection

For this study, a simplified prototype was constructed with the pressure sensor system and without the impedance-sensing system. First, a negative mold of the rigid core was machined out of jeweler's wax. The mold was prepared by routing silicone tubing from the palmar aspect of the fingertip to the dorsal aspect where it was attached to a 3-way stopcock that protruded from the cavity. The mold was then filled with dental acrylic (Hygenic, Perm reline/repair resin). Once the acrylic core had hardened, the silicone tubing was removed, leaving a patent fluid pathway. A pressure sensor (Honeywell, #40PC015G1A) and a 10mL syringe were attached to the remaining ports of the 3-way stopcock. The elastomeric skin (Smooth-On #PMC744, 45 durometer) was dip-coated on the finger surface and allowed to cure. To achieve the adhesion of the skin to the nail bed, mold release (polyvinyl alcohol) was applied to all surfaces of the skin except this area where sufficient bonding occurred. Once cured, the finger was carefully filled with distilled water and air bubbles were removed by systematically applying pressure and suction with the syringe. The fluid was returned to atmospheric pressure once all air bubbles had been purged.

To characterize the relationship between fluid pressure and volume, hydrostatic pressure was measured as distilled water was injected in 0.2mL increments up to 1.0mL for 5 trials. To ensure that no leaks were present in the system the finger was filled with 0.6mL of fluid and allowed to rest for three hours. It was concluded that the sensor was adequately sealed after verifying that there was no detectable change in pressure during this time.

C. Data Acquisition and Signal Processing

A bandwidth of 1000Hz was concluded to be more than adequate based on the observed signal response of the sensor during a variety of tasks using an oscilloscope (unpublished). Additionally, this was well beyond the biological vibration sensitivity of the human finger [4], suggesting that frequencies beyond these limits do not provide useful biomimetic tactile information. To eliminate potential aliasing from unexpected interference, data was collected using a first-order, analog low-pass filter with center frequency at 1000Hz and a digital sampling rate of 2500Hz (Nyquist frequency: 1200Hz). Normal and tangential forces applied to the finger were also recorded from a 6-axis force plate (Advanced Mechanical Technology, Inc., Model HE6X6-16). Data were digitized (National Instruments, USB-6218 with LabVIEW 8.0) and analyzed offline (MathWorks, MATLAB and Signal Processing Toolbox).

D. Response to Sliding Motion over a Controlled Surface

To determine the signal response to sliding motion, the sensor was stroked manually over a ridged surface (3mm regular grating) with approximately constant downward force and constant tangential velocity (Fig. 3). The pressure response was analyzed with a Short Time Fourier Transform (STFT) and presented as a spectrogram vs. time. A time window of 80ms was selected to mimic biological grip reflex response times [1]. To simulate a real-time processing

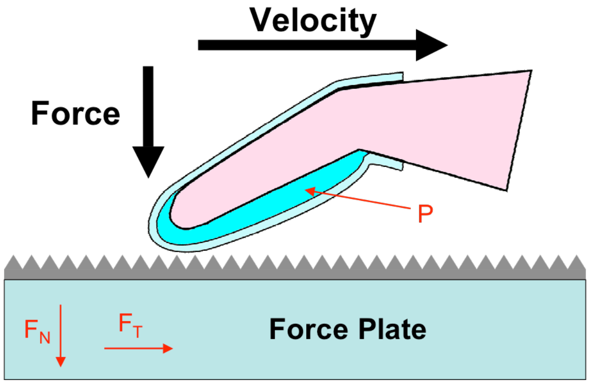

Fig. 3. Experimental procedure. Sensor is slid over a surface while downward force and sliding velocity are controlled manually. Normal and tangential forces are recorded from a force plate simultaneously with the pressure signal. Multiple trials are taken with variations in downward force and velocity.

environment, this window was shifted such that the spectrogram presented at a given time was generated from the previous 80ms of data.

The narrow time window selected for the STFT resulted in a trade-off, sacrificing frequency resolution, an inherit problem with using discrete-time frequency transforms. As a result, high-intensity, low-frequency spectral content leaked into many bands of the STFT, overshadowing any useful spectral information associated with slip. To combat this, a first-order, 5Hz, high-pass filter was used to mitigate the STFT spectral leakage.

The moment of slip is denoted by the transition in the tangential force from a ramp to a plateau. The ramp results from the isovelocity deformation of the skin while it is locked in place by static friction. After slip occurs, the tangential force depends on the constant normal force and dynamic friction. Velocity was estimated by observing the length of time to traverse the 9 cm long test surface.

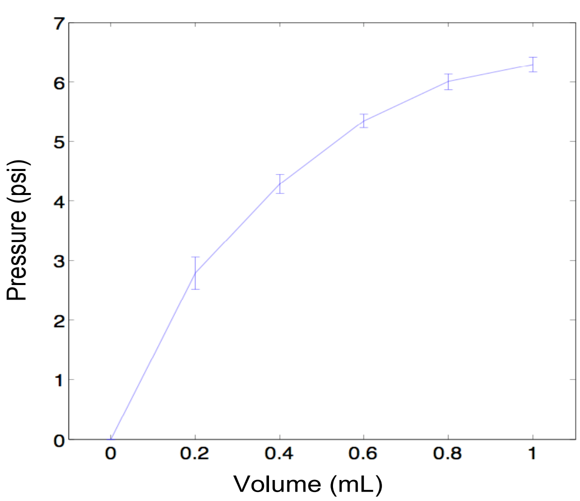

Fig. 4. Pressure vs. Volume curve as fluid is added to the sensor. Experiment was repeated five times with average values being displayed, error bars represent the standard deviation over these trials.

III. Results

A. Pressure Sensor Response to Inflation

The relationship between hydrostatic pressure and fluid volume was consistent over the five trials (Fig. 4). This repeatability over multiple trials suggested that the fluid pathways were adequately sealed.

B. Spectral Features of Contact and Slip

The spectral density plot in Figure 5 shows the general features associated with all test movements. There is an initial pressure spike at first contact with a broad spectrum followed by a relatively silent period as tangential force develops during the stroking motion. The moment of slip is denoted by the vertical dashed line, determined as above. Vibrations from the skin's surface had increased high frequency spectral energy as the finger transitioned into a sliding state. There is a moment of incipient slip at this transition which produces the weak high frequency spectrum just after the dashed line (delayed by the 80ms sampling window). During the steady sliding phase, there are gross rhythmic fluctuations in the force and pressure signals associated with the ridges of the textured surface and a rich set of high frequency harmonics.

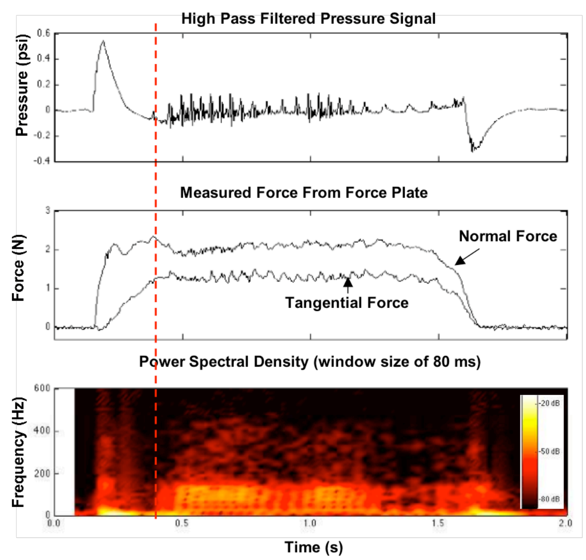

Fig. 5. Demonstration of sliding vibration sensation. As the finger makes contact with a surface, tangential force begins loading until it reaches the plateau at which it begins to slip. The red dashed line indicates the time of slippage. High-frequency spectral power from 30-200Hz appears to be a reliable indicator of sliding while loading and unloading regions are indicated by increases in all frequency bands.

C. Effects of Force and Velocitya

Surprisingly, the spectrograms appeared to be similar in distribution, albeit increasing in general intensity, for higher forces and velocities (Fig. 6&7). Spectrograms resulting from similar sliding movements over differently textured surfaces appeared to have distinctive patterns, but this has not been analyzed systematically.

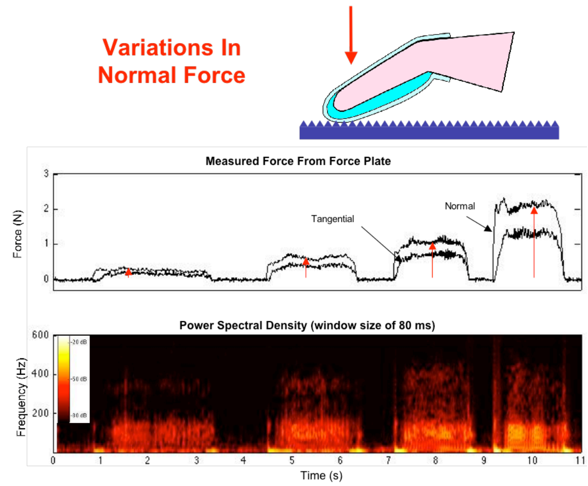

Fig. 6. Increasing downward force while sliding in subsequent trials. Downward force was determined by plateau height of normal force for these four trials while attempting to maintain a consistent sliding velocity. While increasing downward force increases the general spectral intensity no obvious shifts in spectral content were observed.

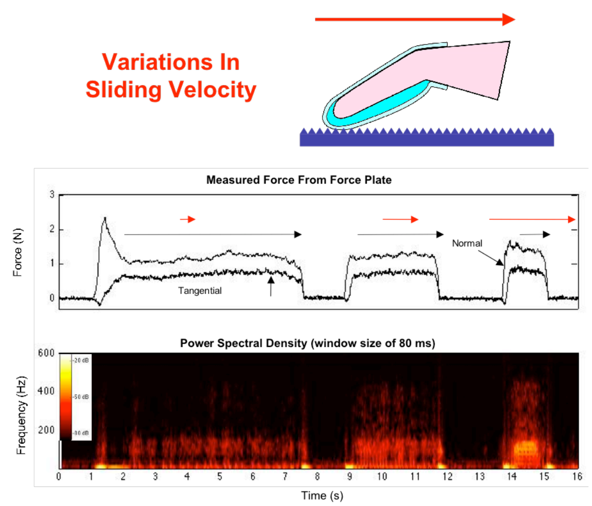

Fig. 7. Increasing sliding velocity in subsequent trials. Velocity (red arrows) was estimated by the amount of time (black arrows) taken to traverse a surface of constant length. Throughout these trials downward force was kept constant. Surprisingly, changes in velocity did not produce noticeable shifts in spectral content indicating that this frequency band is a strong indicator of slip regardless of sliding velocity.

IV. Discussion

A. Relationship Between Fluid Pressure and Volume

Having a defined fluid pressure to volume relationship for a sensor of this type allows for a quick and accurate measurement of fluid volume. It is envisioned that the DC pressure component of the signal can be used to detect leakage and determine if the skin is in need of replacement. This illustrates one advantage of using a piezoresistive pressure sensor as opposed to a piezoelectric pressure sensor, which cannot detect resting pressures.

B. Dynamic Response of the Sensor

As predicted from sound conduction in a fluid, the remote pressure sensor is highly sensitive to microvibrations of the skin. This suggests an opportunity to optimize the shape and mechanical properties of this skin so that it generates more distinctive patterns of such microvibrations for the events and objects to be discriminated. In the current prototype, the outer surface of the skin is smooth, whereas biological fingertips have regular patterns of ridges with 0.3-0.5mm spacing. The mechanical interactions between these ridges and variously textured objects presumably give rise to temporospatial patterns of microvibration that are sensed by the high frequency mechanoreceptors of the glabrous skin. It is not difficult to create such textures by molding elastomers against surfaces machined into a negative of the desired texture [17]. The generation and propagation of such microvibrations across a prosthetic skin and through the fluid to our pressure tranducer is likely to depend on the size and spacing of these molded surface features and the thickness and viscoelasticity of the polymer from which the skin is formed.

While these results provide promising preliminary findings, additional experiments are currently underway to characterize the ability of this design to detect incipient slip. The microvibrations associated with the release of individual skin ridges are likely to be smaller and less coherent than those associated with continuous sliding over a textured surface.

C. Applications

1) Slip Detection for Grip Control

When slid over a textured surface, our biomimetic sensor provides robust, high-frequency, spectral output. This sensory information should be useful for detecting lateral slips in a timely manner such that object-stabilizing grip adjustments can be generated similar to spinal reflexes in the biological hand [3]. With this approach, grip force can be increased at the onset of slip, making possible advanced prosthetics that behave more like the natural hand and are thus easier to control via slower visual feedback.

It should be noted that signal processing parameters, such as the duration of the STFT window (and thus increased response time), will affect the spectral analysis results. Reducing this response time window will reduce the resolution in the frequency domain, making it difficult to distinguish high-frequency spectral content from low-frequency spectral content, but making it faster to detect the onset of the weak vibrations associated with incipient slip.

2) Autonomous Texture Discrimination

We observed (unpublished results) that skin-surface interactions give rise to distinctive “spectral signatures” for this sensor. When sliding our prototype over different surfaces and then replaying the signals (which are in the audible band) through a speaker it was possible to distinguish different surfaces by their tone, much like the human finger can distinguish textures by touch. Further experimentation into how this can be optimized is currently underway.

For the purposes of texture discrimination in robotic applications, the problem becomes more difficult without the spectral analyzing capabilities of the human brain. However, it is proposed that a robotic manipulator with the goal of texture discrimination could make slow exploratory movements similar to biological exploratory movements. These slower movements do not require the same rapid response time as grip reflexes, therefore a wide-windowed STFT can be used for high spectral resolution which is likely to play a key role in artificial texture recognition.

3) Conscious Haptic Feedback

It should be possible to drive a mechanical vibrator with the waveforms detected by our pressure transducer. The vibrator could be located on the intact skin on the residual limb of an amputee or incorporated into the manipulandum of a teleoperated robot. The signal processing would then be performed by the central nervous system.

V. Conclusions

This initial report suggests that hydrophonic sensing can provide a rich source of information about tactile events that are important for the identification and manipulation of everyday objects. Additional experiments are underway to investigate the effects of the design and mechanical properties of the elastomeric skin on the generation of pressure waves and their transduction by the remote sensor. The general design of the finger should provide a relatively inexpensive, robust and easily repaired appliance for use in a wide range of environments.

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