Chapter 18
Dynamic Tactile Sensing

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Abstract Dynamic tactile sensing is an important capability for interacting with the world to identify textures and identify contact events such as objects making and breaking contact with the skin and rolling or slipping on the fingers. It is also used for identifying friction between the fingers and a grasped object and regulating the grasp force accordingly. Humans are endowed with multiple types of mechanoreceptors capable of detecting dynamic events with frequencies in the tens or hundreds of Hz. Increasingly, robots are also being equipped with tactile sensors capable of detecting dynamic phenomena, using a variety of different transducers depending on application-specific design considerations. Advances in electronics have made it possible to do the requisite amplification, signal processing and communication within the hand, with improved performance and greatly reduced wiring in comparison to early efforts.

Keywords Active sensors · Ampliers · Capacitive sensors · Contact motion · Design principles · Dynamic range · Frequency response · Human sensing · Instrumentation · Mechanoreceptors · Optical sensors · Piezoelectric · Psychophysical tests · PVDF · Skin · Skin acceleration · Sliding · Slip · Strain rate sensor · Stress rate sensor · Vibration

1 Introduction

If you press your finger against the corner of a table, you can feel the corner for as long as you hold your finger in place. In contrast, if you rest your finger gently on the table surface you feel relatively little, until you start moving it gently back and

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forth. Suddenly, the texture of the tabletop is apparent, including how dusty it is and whether it has any fine scratches or slippery patches. These sensations are provided by dynamic, or "fast acting" tactile sensors including the Pacinian corpuscles and Meissner endings [1, 2].

Normally, we integrate the signals from fast- and slow-acting mechanoreceptors to give us a comprehensive picture of surfaces, contact events and other conditions important for exploring and manipulating objects. However, even without local contact sensing—for example when we work with tools like scissors or pliers—we can use the vibrations sensed by our Pacinian corpuscles to tell us about events at the tool tip and the textures of surfaces that the tools are interacting with [3, 4].

Dynamic tactile sensing is also useful for event detection. When we grasp an object, it takes a short while for the forces to ramp up to a perceptible level. In contrast, the skin immediately experiences a large deceleration at the instant of contact. Even gently brushing against a soft surface, such as a silk scarf or the fur of an animal, elicits ample dynamic sensation, although the forces and pressures are very small. Another indication of the importance of vibration sensing for event detection is the ubiquity of small vibrating motors in cell phones, pagers and gaming consoles. We are "wired" to respond to vibrational event cues.

One kind of event that is particularly important for dexterous manipulation is the onset of sliding. When humans grasp and manipulate objects, they maintain a consistent margin of safety with respect to the minimum grasp force [2]. The regulation of the grasp force is informed by small vibrations that accompany incipient slippage. If a person cannot sense these vibrations, for example due to the application of an anesthetic, or peripheral neuropathy, or simply because the fingers are getting numb due to cold, the grasp force will gradually relax and a grasped object may be dropped.

In summary, dynamic tactile sensing is an indispensable part of human grasping and manipulation, and of our tactile interaction with the world around us. In robotics, it has received comparatively little attention relative to pressure and force/torque sensing. However it has the potential to be equally useful as robots become more adept at controlling forces on grasped objects and more responsive to changes in sensed forces and vibrations when interacting with the environment.

The following section briefly reviews the current understanding of dynamic tactile sensing in humans and the insights that can be drawn for dynamic tactile sensing in robotics and teleoperated devices. Section 3 reviews progress in developing dynamic tactile sensors for robots, examining the different operating principles employed and their advantages and disadvantages for responding to different types of phenomena. Section 4 then examines the basic characteristics of dynamic tactile sensing in more detail, using an example to illustrate some of the issues regarding mechanical design, transduction principles and signal processing. Section 5 concludes with some observations about the nature and utility of dynamic tactile sensing and challenges for future widespread use in robotics.

2 Dynamic Tactile Sensing in Humans

The human skin is endowed with fast- and slow-acting mechanoreceptors (Fig. 1). The fast-acting (FA) mechanoreceptors respond strongly to high-frequency signals and events characterized by accelerations, vibrations or rapid changes of the strain in the skin. However, if a force is imposed and then remains constant, they produce an initial flurry of spikes that quickly subside. In contrast, the slow acting (SA) mechanoreceptors continue to respond to steady skin deformation.

From the perspective of robotic dynamic tactile sensing, the FA mechanoreceptors are particularly of interest. The relatively superficial FA-I mechanoreceptors, which include the Meissner corpuscles, have an approximate frequency range of 5–50 Hz and a density of over 100/cm^2 in the fingertips [1]. They are most responsive to changing contact conditions, as when a finger makes or breaks contact, or when an object slips over the finger surface. Indeed, slippery surfaces produce more excitation than rough ones [2]. Because of neural branching, and how FA-I receptors are attached to the skin and subcutaneous tissue, contact events affect not only receptors immediately at the contact site but also those nearby. Timing differences in the first spikes produced by these neighboring FA-I receptors can provide information about the shapes and type of contacts even as contacts are still being made, providing information of immediate use in controlling grasp forces. In addition, because each mechanoreceptor responds most strongly to a particular direction, it is possible to ascertain something of the shear stress distribution and the overall direction of force at the contact [5].

In comparison, the FA-II mechanoreceptors, or Pacinian corpuscles, have a broad receptive field and respond strongly to vibrations in the range of 50–500 Hz anywhere in the hand. They are excited, for example, by the vibrations of a tool or object held in the hand as it contacts or drags over surfaces in the environment [2].

Many events will excite multiple types of mechanoreceptors. For example, the act of grasping an object will initially excite the FA-I mechanoreceptors as the skin deforms. Vibrations arising from the contact will also be picked up by the FA-II

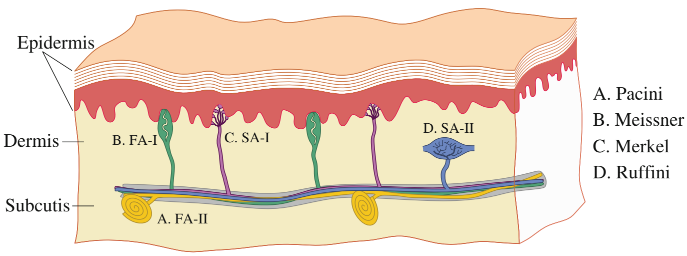


Fig. 1 Cross section of human skin showing slow-acting (SA) and fast-acting (FA) mechanoreceptors, with small (Type I) and large (Type II) receptive fields. Receptors near the surface have smaller receptive fields while those deeper respond to stimuli over a broader area. The superficial FA-I and deeper FA-II mechanoreceptors each have approximate analogs in robotic dynamic tactile sensing

mechanoreceptors. The SA-I mechanoreceptors will also respond to the continued deformation of the skin.

Given that friction is essential for manipulating objects, it is not surprising that humans are quite good at quickly determining the friction conditions associated with handling an object. Reacting to dynamic tactile cues, humans maintain a consistent margin of safety (10–40 % above the minimum grasp force) when handling objects.

Another commonly noted feature of human mechanoreception is its wide dynamic range, defined here as the ratio between the largest and smallest resolvable stimulus. The neural response typically follows a power law: $R \propto S^b$ where R is the response, S is the stimulus magnitude and b is an exponent that averages around 0.7 in many cases [6]. However the variation in intensity reported by subjects in psychophysical tests is often nearly linear, suggesting that the neural and cortical systems compensate for the nonlinear response. One potential advantage of nonlinear response with $b < 1$ is a greater ability to discriminate between low stimulus levels (e.g. a light touch) without quickly saturating for large stimulus levels. At the lowest levels, FA-I mechanoreceptors can detect dynamic skin displacement amplitudes as small as 10 μm.

In summary, tactile sensing in humans is multi-modal, with different kinds of mechanoreceptors specialized for responding to different kinds of phenomena, but also highly integrated. Further, the lessons taught by human mechanoreception can provide insight into the design of robotic dynamic tactile sensing systems.

3 Developments in Robotic Dynamic Tactile Sensing

The advantages of dynamic tactile sensing have been noted in robotics as well as in biology, although dynamic sensors remain a relatively small part of the overall literature on robotic tactile sensing. Broadly speaking, dynamic tactile sensing includes several categories of sensors that are either meant to *detect* motion or incipient motion (slippage), or that *utilize* motion of the fingertips to produce results. A few other sensors are dynamic in the sense that they are actively stimulated, and monitor a change in impedance as they contact objects or surfaces. Finally, there are tactile array sensors that, while not inherently designed to detect or utilize motion, have sufficiently fast mechanical response, and can be sampled rapidly enough, to provide dynamic information as contact conditions change. Examples from of these categories are discussed below.

Motion detection sensors: Among the earliest dynamic tactile sensors were small rollers attached to encoders to detect motion at the fingertips [7, 8]. Other motion-detecting sensors include whiskers, akin to the vibrissae of animals [9, 10]. Still other contact motion-detecting sensors use a transduction technique that is particularly sensitive to motion—for example, a fabric with conductive yarns, for which large changes in resistance can occur in responses to contact movement [11].

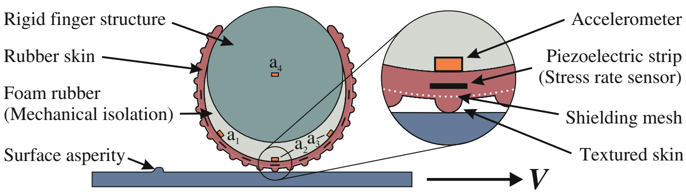


Fig. 2 Cross section of robotic skin, adapted from [12–14], showing accelerometers mounted to the skin and partially isolated from the finger structure by a compliant layer. Small piezoelectric strips embedded in the skin provide localized dynamic response to changes in skin stress. A flexible grounded layer of conductive fabric is added for shielding from electromagnetic interference

Accelerometers: A rough analog to human FA-II mechanoreceptors can be obtained by attaching small accelerometers to the skin (Fig. 2). These can provide large signals when the fingers make or break contact with an object or when an object starts to slip. When part of a suite of tactile sensors, they can be used to detect important events in manipulation tasks (e.g. fingers make or break contact with an object, an object is lifted or replaced on a table top, or slippage occurs) [12, 15].

One potential drawback to accelerometers is that they are excited by all kinds of vibrations, including those emanating from the drivetrain in the robot hand and arm. One way to mitigate this effect is to mount the accelerometers directly to an outer skin, separated from the finger structure by a layer of soft foam or similar material, so they are partially isolated from the finger structure and respond primarily to vibrations or accelerations of the skin itself during manipulation. It can also be useful to compare the signals from accelerometers located immediately at the contact site and nearby on the fingertip, as shown in Fig. 2; the neighboring accelerometers will respond to microslips at the periphery of the contact patch before gross sliding occurs [16].

strain rate sensors: While accelerometers respond broadly to all kinds of vibrations in the hand, a more selective response can be obtained by embedding piezoelectric or other strain rate transducers (also called stress rate transducers, because the strains are produced by stresses in the skin), producing a directional response to changing stresses. PVDF, a flexible piezoelectric film, is particularly useful in this context. Figure 2 shows PVDF strips embedded in an elastomeric skin.

A useful circuit for employing PVDF as a stress rate sensor is depicted in Fig. 3. Two thin strips of metallized, poled PVDF are laminated with opposite polarity so that the outer metallic surfaces are grounded for electromagnetic shielding. A large (approximately 1 MΩ) feedback resistor R_f, and amplifier servo the voltage across the film to zero, minimizing leakage effects. The film has different piezoelectric constants for each direction: $\mathbf{d} = [d_1\, d_2\, d_3]$ where the effect in the d_3 direction, perpendicular to the film, is strongest, the effect in the d_1 direction is also strong, and opposite to d_3, and the constant in the d_2 direction is much weaker. Thus, for triaxial stress, the charge, q, is

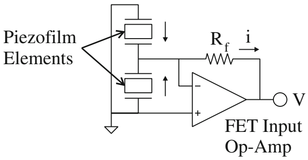


Fig. 3 Circuit for utilizing piezoelectric PVDF film as a stress rate sensor. Two pieces of film are laminated with opposite polarity and outer conductive surfaces grounded, to reduce noise (adapted from [13])

$$q = A\mathbf{d} \cdot \sigma \tag{1}$$

where $\sigma = [\sigma_1\,\sigma_2\,\sigma_3]^t$ and A is the area of the film, typically on the order of 0.5–1 cm^2. Since $i = d\sigma/dt$ the output of the circuit is proportional to the rate of change of stress:

$$v = AR_f\mathbf{d} \cdot \frac{d\sigma}{dt}. \tag{2}$$

As the fingertip drags over small surface features, the PVDF sensors provide large signals in proportion to the local rate of change of stress in the skin [13, 14]. In this manner, stress-rate sensors exploit motion. If the finger slides along a surface with a velocity $v = dx/dt$, the signal will be a function both of stress gradients within the skin, which depend on the sharpness of features on the object surface, and the sliding velocity: $d\sigma/dt = (d\sigma/dx)(dx/dt)$. This effect allows a finger with a single stress rate sensor to scan across an object, detecting small features such as ridges or bumps, with profiles as small as a few micrometers high [13].

It is also possible to instrument piezoelectric sensors with charge amplifiers so that they produce an output proportional to the local stress rather than the stress rate, although their high impedance makes them particularly suited for measuring dynamic forces [17–25]. However, with care they can even be used to measure static loads [26]. There is also the possibility to integrate PVDF directly with MOS circuitry for miniaturization and high signal/noise ratio [27, 28]. Local integration of amplifying elements could greatly reduce the complexity of wiring and readout electronics in this class of sensor.

Other transducers can also be used as stress or strain-rate sensors. For example, Kikkwe et al. [29] demonstrate a device using a viscous fluid and baffles that responds only to transient changes in loading.

Actively stimulated sensors: Capacitive and piezoelectric transducers can also function as actuators, leading to the possibility of actively stimulated tactile arrays. Variations include ultrasonic arrays that measure changes in thickness as a soft skin makes contact with surfaces [30], stimulated piezoelectric probes [31] or resonant cavities [32, 33], piezoelectric array sensors [34] and pneumatically driven cells with piezoresistive elements [35].

Other sensors with fast response: There are a number of sensor designs that, while not designed specifically to detect or utilize motion, can nonetheless produce dynamic information by virtue of having a frequency response on the order of tens or hundreds of Hz. The performance of these sensors depends both on the available sampling or addressing rate for individual elements and, especially, on their mechanical construction. A particular challenge is to achieve a useful frequency response of 50 Hz or greater with soft materials. The sensors need to have low hysteresis, which in turn requires that they use materials without significant damping or viscoelasticity, and that they be constructed as a single bonded unit, instead of assemblies with internal contacts having friction or adhesion. Examples of such sensors include capacitive arrays that utilize a silicone rubber foam or molded pattern, bonded to a conductive outer skin for shielding [36–41]. Other sensors that employ an incompressible low-viscosity fluid can also provide dynamic signals [42].

With sufficient response, small arrays of piezoresistive or capacitive sensors can also be used in a scanning mode, to discriminate among different textures [43–46] or to detect incipient object slippage based on the ratios of strains as an elastic fingertip is pressed against a surface and loaded in shear [47]. Optical tactile sensors can also detect changing textures and slip, depending on the frame rate of the associated optical imaging device [48]. In many cases, mechanical design features in the skin and how the sensors are connected to the skin can be used to enhance the sensor response. For example ridges can produce a “plucking” action that enhances response as a sensor slides over small features [49, 50]. More generally, texturing the robot skin leads to more predictable sliding behavior, often with a characteristic vibration frequency [13].

4 Dynamic Tactile Sensing Design Considerations

As the previous section reveals, there are various ways to achieve dynamic tactile sensing. However, they share a number of common design principles:

- low hysteresis for good dynamic response
- mechanical isolation to measure forces or motions at the location of interest only
- sensitivity aligned with force direction of interest, i.e. normal forces may be important for contact, whereas normal and shear forces may be important for friction estimation
- strong event correlation, e.g. fingerprint ridges vibrating at a characteristic frequency during slipping.

In addition, dynamic tactile sensors share a number of basic considerations with all tactile sensors:

- coverage and density
- repeatability
- minimum resolvable force or acceleration
- maximum force or acceleration before saturation

- packaging and robustness
- provisions for sampling and signal routing.

Unlike a CMOS imaging chip, a tactile sensor must be curved, compliant, flexible (especially around joints), tough enough to survive repeated impacts and scrapes, and distributed over large surface areas. As a result, wiring becomes a challenge. These factors have conspired to make progress in tactile sensing slower than in computer vision.

Achieving a suitable combination of the (sometimes competing) objectives listed above typically requires a design that is customized to a particular application. Thus the sensors and skin for a fingertip are different from those on an arm. To illustrate some of the design considerations in more detail, the following section considers a capacitive tactile array designed to provide both steady, or slow-acting, and dynamic, or fast-acting, performance.

4.1 Dynamic Sensing Example

4.1.1 Sensor Design

A capacitive transducer can be constructed as in Fig. 4 with two conductive plates separated by a compressible dielectric medium. As forces are applied normal to the surface, the gap reduces, producing a change in capacitance governed by the well known parallel plate capacitor equation:

$$C = \frac{\epsilon A}{d} \tag{3}$$

where C, ϵ, A, and d are the capacitance, dielectric constant, plate area, and separation, respectively. With this simple structure, it can be seen that the sensitivity to small changes in force, F, depends on the initial plate separation, d_0, and the dielectric stiffness. Let $F = k(d_0 - d)$ for small deflections, where the

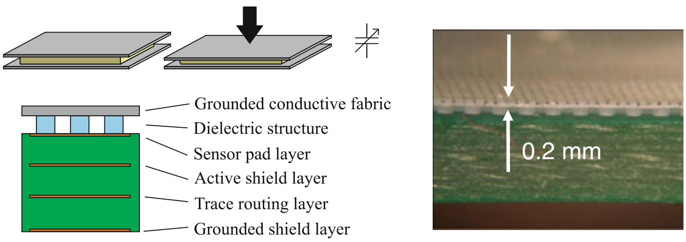


Fig. 4 **a** Two conductive plates are separated by an elastic dielectric. As force is applied, the gap between the plates reduces, changing the capacitance. **b** In practice, additional shielding layers are usually required for immunity to noise and to prevent the sensor from responding in part as a proximity sensor. **c** In construction, the dielectric and upper conductive layer can be quite thin

$k = AE/d$ and E is the effective modulus (i.e. the average modulus for initial compression, given that the dielectric may not be homogeneous). Then for initial contact:

$$\lim_{d \to d_0} \frac{\partial C}{\partial F} = \frac{\epsilon}{E d_0} \tag{4}$$

For sensitivity to small forces, E should be low. A low density open cell foam can be quite compressible and indeed, yields a high sensitivity. Unfortunately, such a foam also tends to have significant hysteresis, which reduces the dynamic response. A better solution for dynamic response is to use a pattern molded from an elastomer such as silicone rubber, which has low viscoelasticity and low hysteresis in comparison to other polymers (e.g. urethanes) of similar stiffness [51, 52]. The other way to increase sensitivity is to make the sensor quite thin (small d_0), as shown in Fig. 4 at right. In this example, the dielectric consists of a dense array of short elastic posts, bonded at the base and top, to create a monolithic structure with low hysteresis and moderate stiffness (approximately 1 MPa per mm of compression) for initial deflections. However the stiffness increases for large deflections leading to a nonlinear response, which can be useful for delaying saturation at high loads.

The thin sensor is intended to be located beneath a thicker artificial skin, which provides the desired compliance and has the added advantage of "blurring" the pressure distributions associated with sharp contacts. This well known effect can lead to higher accuracy in resolving the locations of isolated contacts for a given taxel size [53, 54]. However, if one is interested in dynamic response, the skin material, like the dielectric, should be chosen to avoid significant hysteresis and viscoelasticity. At higher frequencies (e.g. above 100 Hz for the sensor shown in Fig. 4), the mass of the skin should also be considered.

4.1.2 Instrumentation and Signal Processing

Many options are available for measuring the change of capacitance in a sensor like that shown in Fig. 4. With the advent of smart cell phones with capacitive touch screens, an attractive solution is to use dedicated integrated circuits (ICs) that provide active shielding, high sampling and analog/digital conversion rates, filtering and communication over a high-speed bus. In particular, a solution used by the authors, and by others for sensors on the iCub robot [39, 40], is the Analog Devices AD7147-1. With this IC, small arrays of n sensors can be sampled at $1200/n$ Hz, well into the range of human FA-I and FA-II sensitivity. Multiple arrays can be controlled by small microcrontrollers located adjacent to the sensors [41].

Figure 5 shows a three fingered robot hand with tactile sensors as described above, pulling a thin object out of a slot. It is of interest to see whether object/hand slips can be distinguished from object/world slips, something that humans do easily using their suite of mechanoreceptors, as discussed in Sect. 2. In the present case, it is difficult to distinguish between the two cases using accelerometers or individual piezoelectric sensors, as both types of slippage excite numerous vibrations in the skin. However, by comparing the average power per taxel with the maximum power, a distinction emerges.

Let $p_n^{(i)}$ be the nth sample from the ith sensor on the finger surface. The sum of signals over the surface is

$$s_n = \sum_i p_n^{(i)} \tag{5}$$

and the power in a given frequency band is given by

$$S(f, w) = \sum_{k=f-w}^{f+w} S_k \tag{6}$$

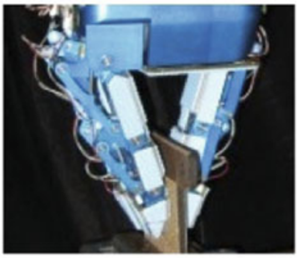
$$M(f, w) = \max_i \sum_{k=f-w}^{f+w} P_k^{(i)} \tag{7}$$

where S_k and $P_k^{(i)}$ are the power in the kth frequency bin from the Discrete Fourier Transform of s and $p^{(i)}$, respectively, and f and w are the center and half-width, respectively, of the frequency band to consider. The sensor with the most power in the band of interest is used to calculate M.

Figure 5 shows the results of taking the ratio $S(f, w)/M(f, w)$ for $w = 7.5$ Hz and a range of frequencies, for a group of taxels at the fingertips. The taxels were sampled at 300 Hz and filtered using a discrete 1st order Butterworth high-pass filter with a cutoff frequency of 5 Hz, and power spectrum was computed using the FFT. The power spectra were averaged across 10 trials to give an estimate of a "typical" power spectrum for the manipulation trials. What stands out in Fig. 5 is that over a range of frequencies, the ratios of the sum and the maximum power are typically different for object/hand and object/world slips. The insensitivity to frequency suggests that such a metric should hold for a range of range of speeds and textures [41].

4.1.3 Instrumenting as a Dynamic Sensor

While a single sensor package providing broad frequency response is a highly desirable solution, there may remain advantages to designing a purpose built dynamic sensor for high frequency signals. In such a sensor, the steady state or "DC" component of the signal can be ignored. In the case of the capacitive tactile sensor, the direct analog output from the sensor may be high pass filtered prior to amplification, potentially allowing for much higher amplification levels due to the lack of a large bias offset that would cause premature saturation. This is especially true if there is a mismatch in the required force range at high and low frequencies (i.e. it may be desirable to sense large static loads and light contact events). Furthermore, some mechanical/material properties such as thermal drift will no



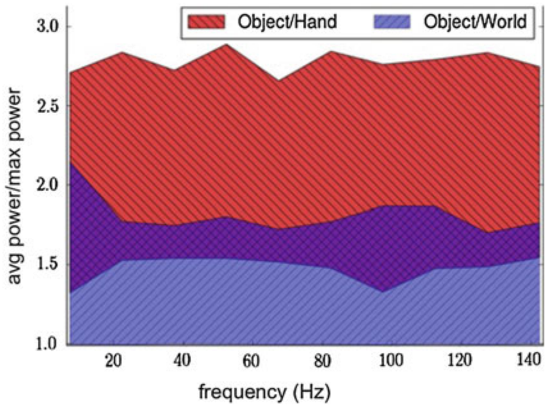


Fig. 5 A robot hand grasps a thin object and pulls it out of a slot; object/hand and object/world slips can occur (*left*). The ratios of average to maximum power for a collection of taxels help to distinguish object/hand from object/word slips, for a wide range of frequencies and a collection of 10 trials (*right*)

longer affect response and a wider group of materials can be considered for mechanical transduction.

An example dynamic sensor circuit for a capacitive transducer is shown in Fig. 6. The schematic is a typical amplifier for a condenser microphone. The circuit provides high dynamic sensitivity due to its high pass filtered input stage and allows correspondingly high gain. The preponderance of microphones in devices such as cell phones means that small and inexpensive microphone amplifier IC's are readily available. The filtering and amplifier circuits can be located adjacent to the transducer allowing for minimal noise coupling from cabling. As seen in Fig. 7, for the same transducer, the response and signal/noise ratio from the microphone circuit are much greater for light dynamic contact events such as dropping or placing a small weight on the sensor surface.

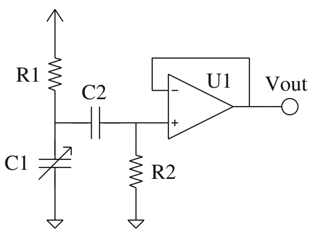


Fig. 6 Condensor microphone circuit that can be used with capacitive sensor. Resistor R1 allows a static bias charge to accumulate on sensor C1 and, in dynamic operation, C1 can be considered to operate in a constant charge condition. C2 and R2 (R2 is typically the input impedance of the amplifier) high pass filter the voltage across C1 prior to amplification. High amplification is possible because the filter removes bias and the amplifier can be located adjacent to transducer to minimize noise

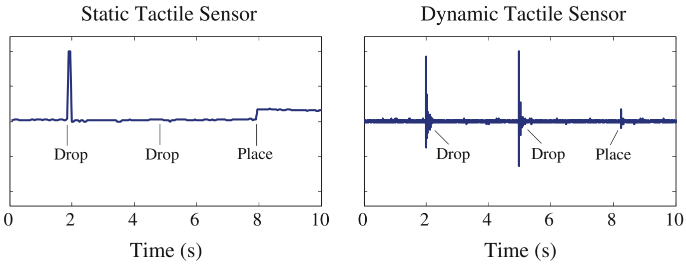


Fig. 7 Data from capacitive sensor in Fig. 4 as 10 g weight is dropped from a few cm and then gently placed on surface (*left*). Data from sensor instrumented using circuit from Fig. 6 for the same loading sequence (*right*)

5 Summary

As the example in this section shows, a common transducer can, with attention to mechanical construction and materials, provide data at frequencies high enough to detect dynamic events such as object slippage. As noted in [15], comparisons of low-pass and high-pass filtered data from a commercially available tactile array, and data from an accelerometer, can be combined to detect various dynamic events in manipulation. As Fig. 5 reveals, the ability to compare correlated and uncorrelated signals from adjacent taxels is also helpful in distinguishing between different kinds of dynamic events in a manner somewhat analogous to the use of groups of FA-I sensors in humans. Finally, the distinction between a tactile array with good frequency response and a dedicated dynamic tactile sensor often comes down to the circuits used to filter and amplify signals. Constructing a circuit that only amplifies high-frequency signals, as in Figs. 3 and 6, allows much greater sensitivity to transient phenomena.

6 Conclusions and Future Challenges

Dynamic tactile sensing is extremely important in human manipulation: it allows us to detect events like contact and slippage, and to distinguish textures and perceive tiny surface features as we slide our fingers over surfaces. Humans use combinations of mechanoreceptors, with different inherent properties, both at the site of a contact and nearby, to distinguish among events like objects slipping in the hand and grasped objects slipping against a surface in the world. As robots emerge from structured and predictable environments like manufacturing they too will increasingly require dynamic tactile sensing to be informed of contact events and changes in texture, friction conditions, etc.

Many approaches are available for dynamic tactile sensing including accelerometers and high-frequency piezoelectric transducers. It is also possible to obtain dynamic information from conventional capacitive, piezoresistive, optical or other tactile arrays provided that care has been exercised in their design and materials choices. However, for the greatest sensitivity to phenomena like a light grazing touch, it is ideal to configure at least some of the transducing elements explicitly as high frequency sensors, permitting high amplification and a high signal/noise ratio for transient forces or vibrations.

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