Multimedia Contents

28. Force and Tactile Sensing

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This chapter provides an overview of force and tactile sensing, with the primary emphasis placed on tactile sensing. We begin by presenting some basic considerations in choosing a tactile sensor and then review a wide variety of sensor types, including proximity, kinematic, force, dynamic, contact, skin deflection, thermal, and pressure sensors. We also review various transduction methods, appropriate for each general sensor type. We consider the information that these various types of sensors provide in terms of whether they are most useful for manipulation, surface exploration or being responsive to contacts from external agents.

Concerning the interpretation of tactile information, we describe the general problems and present two short illustrative examples. The first involves intrinsic tactile sensing, i. e., estimating contact locations and forces from force sensors. The second involves contact pressure sensing, i. e., estimating surface normal and shear stress distributions from an array of sensors in an elastic skin. We conclude with a brief discussion of the challenges that remain to be solved in packaging and manufacturing damage-tolerant tactile sensors.

28.1 Overview

Tactile sensing has been a component of robotics for roughly as long as vision. However, in comparison to vision, for which great strides have been made in terms of hardware and software and which is now widely used in industrial and mobile robot applications, tactile sensing always seems to be *a few years away* from widespread utility. So before reviewing the technologies and approaches available, it is worthwhile to ask some basic questions:

- How important is tactile sensing?
- What is it useful for?
- Why does it remain comparatively undeveloped?

In nature, tactile sensing is an essential survival tool. Even the simplest creatures are endowed with large numbers of mechanoreceptors for exploring and responding to various stimuli. In humans, tactile sensing is indispensable for three distinct kinds of activity: manipulation, exploration and response. The importance of tactile sensing for manipulation is most evident in fine motor tasks. When we are chilled, tasks like buttoning a shirt can become an exercise in frustration. The problem is primarily a lack of sensing; our muscles, snug in our coat sleeves, are only slightly affected but our cutaneous mechanoreceptors are anesthetized and we become clumsy. For exploration, we continually assimilate information about materials and surface properties (e.g., hardness, thermal conductivity, friction, roughness) to help us identify objects. We may have difficulty distinguishing real leather from synthetic leather by sight, but not by touch. Finally, the importance of tactile response, whether to a gentle touch or an impact, is seen in the damage that patients with peripheral neuropathy (e.g., as a complication of diabetes) accidentally do to themselves.

As Fig. 28.1 indicates, the same functional categories apply to robots. However, in comparison to animals, with hundreds or thousands of mechanoreceptors per square centimeter of skin, even the most sophisticated robots are impoverished. One reason for the slow development of tactile sensing technology as compared to vision is that there is no tactile analog to the charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) optical array. Instead, tactile sensors elicit information through physical interaction. They must be incorporated into skin surfaces with compliance, for conforming locally to surfaces, and with adequate friction for handling objects securely. The sensors and skin must also be robust enough to survive repeated impacts and abrasions. And unlike the image plane in a camera, tactile sensors must

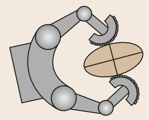
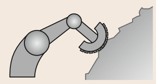
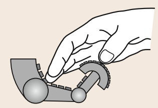
	*Manipulation*: Grasp force control; contact locations and kinematics; stability assessment.
	*Exploration*: Surface texture, friction and hardness; thermal properties; local features.
	*Response*: Detection and reaction to contacts from external agents.

Fig. 28.1 Uses of tactile sensing in robotics

be distributed over the robot appendages, with particularly high concentrations in areas like the fingertips. The wiring of tactile sensors is consequently another formidable challenge.

Nonetheless, considerable progress in tactile sensor design and deployment has been made over the last couple of decades. In the following sections we review the main functional classes of tactile sensors and discuss their relative strengths and limitations. Looking ahead, new fabrication techniques offer the possibility of artificial skin materials with integrated sensors and local processing for interpreting sensor signals and communicating over a common bus to reduce wiring.

There is an extensive literature describing touch sensing research. Recent general reviews include [28.1–4] and these cite a number of useful older reviews including [28.5–7].

28.2 Sensor Types

This section outlines five main types of sensors: proprioceptive, kinematic, force, dynamic tactile, and array tactile sensors, as well as sensors that provide thermal or material composition data. However, the emphasis is on sensors that provide mechanoreception, as summarized in Table 28.1. The most important quantities measured with tactile sensors are *shape* and *force*. Each of these may be measured as an average quantity for some part of the robot or as a spatially resolved, distributed quantity across a contact area. In this chapter we follow the convention of studies of the human sense of touch and use the term *touch sensing* to refer to the combination of these two modes. Devices that measure an average or resultant quantity are sometimes referred to as *internal* or *intrinsic* sensors. The basis for these sensors is force sensing, which precedes the discussion of tactile array sensors.

28.2.1 Proprioceptive and Proximity Sensing

Proprioceptive sensing refers to sensors that provide information about the net force or motion of an appendage, analogous to receptors that provide information in humans about tendon tensions or joint movements. Generally speaking, the primary source for spatial proproceptive information on a robot is provided by joint angle and force–torque sensors. Since joint angle sensors such as potentiometers, encoders, and resolvers are well established technologies, they do not warrant discussion here. Instead, a brief review of proximity sensing via whiskers and antennae as well as noncontact proximity sensing is provided. Force–torque sensors are discussed in greater detail in Sect. 28.2.4.

Table 28.1 Tactile sensor modalities and common transduction types

Sensor modality	Sensor type	Sensor attributes	Advantages	Disadvantages
Normal pressure	Piezoresistive array [28.8–12]	Array of piezoresistive junctions Embedded in a elastomeric skin Cast or screen printed	Suitable for mass production Simple design Simple signal conditioning	Low force thresholds/high sensitivity Frail Signal drift and hysteresis
	Capacitive array [28.13–17]	Array of capacitive junctions Row and column electrodes separated by elastomeric dielectric	Good sensitivity Moderate hysteresis, depending on construction	Complex circuitry
	Piezoresistive microelectromechanical system (MEMS) array [28.18–20]	Silicon micromachined array with doped silicon strain gauged flexures	Suitable for to mass production	Frail
	Optical [28.21, 22]	Combined tracking of optical markers with a constitutive model	No interconnects to break	Requires personal computer (PC) for computing applied forces
Skin deformation	Optical [28.23, 24]	Fluid-filled elastomeric membrane Tracking of optical markers inscribed on membrane coupled with energy minimization algorithm	Compliant membrane No electrical interconnects to be damaged	Complex computations Hard to customize sensor
	Magnetic [28.25]	Array of hall effect sensors		Complex computations Hard to customize sensor
	Resistive tomography [28.26]	Array of conductive rubber traces as electrodes	Robust construction	
	Piezoresistive (curvature) [28.27, 28]	Employs an array of strain gauges	Directly measure curvature	Frailty of electrical interconnects Hysteresis
Dynamic tactile sensing	Piezoelectric (stress rate) [28.19, 29, 30]	polyvinylidene fluoride (PVDF) embedded in elastomeric skin	High bandwidth	Frailty of electrical junctions
	Skin acceleration [28.31, 32]	Commercial accelerometer afixed to robot skin	Simple	No spatially distributed content Sensed vibrations tend to be dominated by structural resonant frequency

Whisker and Antenna Sensors

For many animals whiskers or antennae provide an extremely accurate combination of contact sensing and proprioceptive information. For example, cockroaches can steer themselves along curved walls using only position and rate information from their antennae [28.33]. Other insects and arthropods use numerous small hair sensors on the exoskeleton to localize contacts. Rats perform highly accurate whisking to explore the shapes and textures of objects in their vicinity, with sensor processing performed by a specialized barrel cortex [28.34].

In robotics, this potentially very useful hybrid of proprioceptive and tactile sensing has received comparatively little attention, although examples date at least to the early 1990s [28.35, 36]. In more recent work, *Clements* and *Rahn* [28.37] demonstrated an active whisker with a sweeping motion and *Lee* et al. [28.33] used a passive, flexible antenna to steer a running cockroach-inspired robot. *Prescott* et al. [28.34, 38] have conducted extensive work on active robotic whisking for object exploration and identification, inspired by mammalian models.

Proximity

While proximity sensing does not strictly fall under the category of tactile sensing, a number of researchers have employed proximity sensors for collision detection between a robot arm and the environment; hence, we briefly review these technologies here. Three primary sensor technologies which include capaciflective, infrared (IR) optical, and ultrasonic sensors have been used in this application. *Vranish* et al. developed an early capaciflective sensor for collision avoidance between the environment and a grounded robot arm [28.39]. Early examples of IR emitter/detector pairs in an artificial skin include [28.40, 41]. A more recent design using optical fibers is reported in [28.42], and an adaptation for a prosthetic hand is reported in [28.43]. Other researchers have developed robot skin that includes ultrasonic and IR optical sensors for collision avoidance [28.44]. *Wegerif* and *Rosinski* provide a comparison of the performance of all 3 of these proximity sensing technologies [28.45]. For a further review of some of these sensors, see Chap. 31 on range sensing.

28.2.2 Other Contact Sensors

There are a variety of other contact-based sensors that are capable of discerning object properties such as electromagnetic characteristics, density (via ultrasound), or chemical composition (cf. animals' senses of taste and smell). While this is beyond the scope of the current chapter, Chap. 75, on biologically inspired robots, briefly discusses biologically inspired chemical sensors related to smell and taste. For completeness, thermal sensors and material composition sensors are also briefly discussed below.

Thermal Sensors

Thermal sensing is an important element of human tactile sensing, useful for determining the material composition of an object as well as to measure surface temperatures. Since most objects in the environment are at about the same (*room*) temperature, a temperature sensor that contains a heat source can detect the rate at which heat is absorbed by an object. This provides information about the heat capacity of the object and the thermal conductivity of the material from which it is made, making it easy, for example, to distinguish metals from plastics.

Buttazzo et al. [28.46] note that the piezoelectric polymer used in their tactile sensing system is also strongly pyroelectric, and use a superficial layer as a thermal sensor. Other sensors use thermistors as transducers [28.47–49]. Some systems purposely provide an internal temperature reference and use the temperature differential from the environment to detect contacts [28.50, 51]; however, objects with a temperature the same as the reference will not be detected. Most of these sensors have a relatively thick outer skin covering the heat sensitive elements, thus protecting delicate components and providing a conformal surface at the expense of slower response time.

As a more recent example of thermal sensing, *Engel* et al. [28.52] present a flexible tactile sensor design that includes integrated gold film heaters and RTDs (resistance temperature devices) on a polymer micromachined substrate. *Lin* et al. [28.24] include a thermistor as part of the sensing suite in their artificial fingertip. While there is a high level of integration in these sensors, tradeoffs concerning construction, performance, and protection of sensing elements remain an ongoing challenge.

Material Composition Sensors

There has been some work on sensors for material composition. In analogy with the human senses of taste and smell, liquid and vapor phase chemical sensors could potentially determine the chemical composition of a surface [28.53, 54]. However, the large majority of robotic chemical sensing has involved non-contact sensing of airborne plumes [28.55, 56]. Another sensing modality which provides information about material properties is electromagnetic field sensing, using devices such as eddy current or Hall effect probes to measure ferromagnetism or conductivity [28.57, 58].

28.2.3 Kinematic Sensors

Although they are not generally regarded as tactile sensors, sensors that detect the position of a limb can provide the robot with geometric information for manipulation and exploration, particularly when the limb also includes sensors that register contact events. Examples of combining joint angle sensing and contact sensing with compliant fingers to learn about the configuration of a grasp include [28.59, 60].

28.2.4 Force and Load Sensing

Actuator Effort Sensors

For some actuators such as electric servo motors, a measure of the actuator effort can be obtained directly by measuring the motor current (typically using a sensing resistor in series with the motor). However, because motors are typically connected to robot limbs via gearboxes with output/input efficiencies of 60% or less, it is usually much more accurate to measure the torque at the output of the gearbox. Solutions to this problem include torque load cells and mechanical structures at the robot joints whose deflections can be measured using electromagnetic or optical sensors. For cable or tendon-driven arms and hands it is useful to measure the cable tension – both for purposes of compensating for friction in the drive-train and as a way of measuring the loads upon the appendage [28.61, 62]. When fingers or arms make contact with objects in the environment, cable tension sensing becomes an alternative to endpoint load sensing for measuring components of the contact forces. Of course, only those components that produce significant torques can be measured with accuracy. Chapter 19 on multifingered hands contains more details concerning tendon tension measurement.

Force Sensors

When actuator effort sensors are not sufficient to measure the forces exerted by or on a robot appendage, discrete force sensors are typically utilized. These sensors are found most often at the base joint or wrist of a robot but could be distributed throughout the links of a robot.

In principle, any type of multi-axis load cell could be used for manipulator force–torque sensing. However, the need for small, lightweight units with good static response eliminates many commercial sensors. The design of force sensors for mounting above the gripper at the wrist has received the most attention [28.63, 64], but fingertip sensors for dextrous hands have also been devised. Often these sensors are based on strain gauges mounted on a metal flexure [28.65–67] which can be fairly stiff and robust. *Sinden* and *Boie* [28.68] propose a planar six axis force–torque sensor based on capacitive measurements with an elastomer dielectric. Design considerations for force sensors include stiffness, hysteresis, calibration, amplification, robustness, and mounting. *Dario* et al. present an integrated fingertip for robotic hands integrated FSR (force sensing resistor) pressure array, piezoceramic bimorph dynamic sensor, and force–torque sensor [28.29]. More recently *Edin* et al. [28.69] have developed a miniature a multi-axis fingertip force sensor (Fig. 28.2). For applications where immunity to electromagnetic noise is desirable, *Park* et al. [28.70] present a robot fingertip with embedded fiber optic Bragg gratings, used as optical strain gages. *Bicchi* [28.71] and *Uchiyama* et al. [28.72] consider the optimal design of multi-axis force sensors in general.

Information from the force sensors can also be combined with knowledge of fingertip geometry to estimate contact location, as implied in Fig. 28.3. This method of contact sensing is referred to as *intrinsic tactile sensing* and was first presented by *Bicchi* et al. [28.73]. A comparison between intrinsic and extrinsic contact sensing

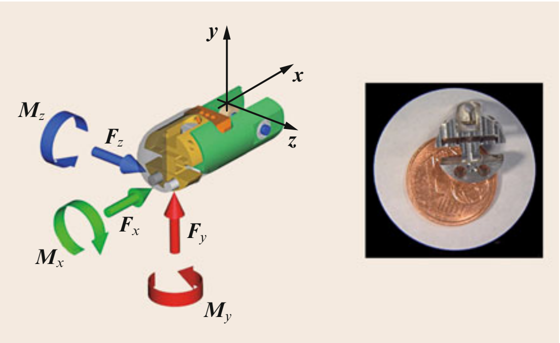


Fig. 28.2 Miniature fingertip force–torque sensor for a prosthetic hand (after [28.69])

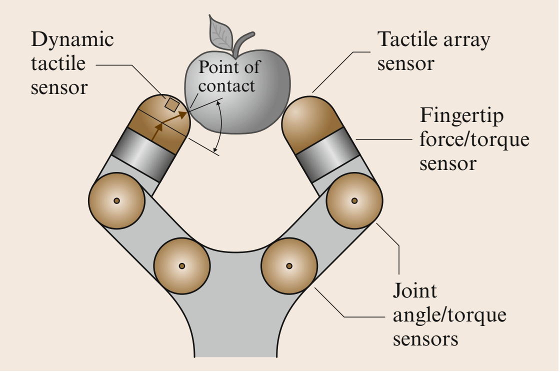


Fig. 28.3 Robot hand with fingertip force and tactile sensing. Information from the force sensors can be combined with knowledge of fingertip geometry to estimate contact location, referred to as *intrinsic tactile sensing*

(i. e., using distributed contact sensors) is presented by *Son* et al. [28.74]. This topic is discussed further in Sect. 28.3.1.

28.2.5 Dynamic Tactile Sensors

Taking a cue from the role of fast-acting or dynamic tactile sensors in human manipulation [28.75], researchers have developed dynamic sensors for slip detection and for sensing textures and fine features.

Early slip sensors based on displacement detected the motion of a moving element such as a roller or needle in the gripper surface [28.76, 77]. Subsequent work has typically used accelerometers or other sensors that are inherently sensitive to small, transient forces or motions. Early examples include [28.31, 78–80]. Many subsequent contributions are reviewed in [28.81].

For the case of hard objects held in metal grippers, acoustic emissions may reveal slip [28.82]. Because these signals are at very high frequency (over 100 kHz) they can be useful for distinguishing among different kinds of contact events in noisy environments [28.83]. Another approach for improving the signal/noise robustness of dynamic sensing is to use an actively stimulated sensor and measure the change in response as contact conditions change [28.84, 85].

For grasp force control, it is especially useful to detect incipient slips, which are accompanied by small, localized vibrations, or micro-slips, at the periphery of a finger/object contact region before gross sliding occurs. The challenge is to distinguish these from other events that produce vibrations [28.86–89].

For detecting features and fine surface features it can be effective to use small fibers, a skin with fingerprint-like ridges, or a stylus that drags over the surface like a fingernail [28.46, 90, 91].

Because many dynamic tactile sensors only produce a transient response, they are often combined with pressure sensing arrays or force sensors to provide a combination of low frequency and high frequency tactile sensing [28.24, 29, 32, 46, 89, 92, 93]. An alternative, which can be simpler from the standpoint of sensor integration, is to use conventional pressure sensing arrays for slip detection. In this case, the array resolution and scanning rate must be sufficient to detect motion or incipient motion quickly, to prevent grasp failures. Fortunately, this is becoming increasingly feasible [28.19, 81, 94, 95]. VIDEO 14 shows an example of dynamic tactile sensing.

28.2.6 Array Sensors

Hundreds of designs for tactile array sensors have appeared in the literature in the last 25 years, and many of them are designed for use with dextrous hands. In terms of transducers, the fundamental requirement is to unambiguously recover either the shape or pressure distribution across the contact. Shape sensing requires a compliant skin, which can also have advantages for grasp stability (see Chaps. 37 and 38 on contact modeling and grasping). Examples of shape-sensing tactile arrays include [28.23, 24]. However, the far more common approach is to measure subsurface strains, which can be correlated with surface pressure distributions, as presented by *Fearing* and *Hollerbach* [28.96] and discussed further in Sect. 28.3.2.

Contact Location Sensors

The simplest and perhaps most robust tactile arrays provide measurements solely of contact location. Some such sensors utilize a membrane switch design like that found in keyboards [28.97]. As another example, a robust two-dimensional (2-D) switch array can be embedded in a prosthetic hand [28.69]. Some optical tactile sensors have also been used primarily as contact location sensors. *Maekawa* et al. [28.98] used a single optical position sensing device (PSD) or a CCD camera array to detect the position of scattered light off of a hemispherical optical wave guide fingertip with a silicone rubber cover. Light is scattered at the locations of contacts. With a textured skin, the magnitude of the force can also be estimated, as the contact area grows in proportion to the pressure. However, an issue with fingertips that use a compliant skin covering a hard substrate is that adhesion between the two materials results in hysteresis. In addition, when the fingertip is dragged over a surface, the friction can produce a shift in the estimated contact position.

Pressure Sensing Arrays

Capacitive Pressure Sensing Arrays. Capacitive pressure sensing arrays are one of the oldest and most common tactile sensor types. Some of the earliest analysis of such sensors is presented by *Fearing* [28.99] for capacitive arrays embedded into a soft robot fingertip. The arrays consist of overlapping row and column electrodes separated by an elastomeric dielectric, forming an array of capacitors. A change in capacitance results from compressing the dielectric between row-column plates at a particular intersection. The equation for capacitance, based on the physical parameters, is expressed as $C \approx \epsilon A/d$, where ϵ is the permittivity of the dielectric between the plates of the capacitor, A is the area of the plates, and d is the spacing between them. Pressing on the skin reduces the plate spacing d, thus providing a linear response with displacement. Through appropriate switching circuitry, a region of a sensor array can be isolated at a particular row/column intersection. Examples of similar capacitive tactile arrays can be found in [28.100, 101] and commercially [28.14]. Large capacitive arrays have also been developed to cover the arms of a robot [28.15–17]. A woven fabric with capacitive sensing junctions is reported in [28.102].

With a suitable dielectric and plate design, capacitive arrays can be robust, have a large dynamic range (ratio between minimum and maximum detectable pressure) and low hysteresis, which is desirable for fast response. However, a common problem is the need to shield the array from stray capacitance effects (e.g., from an approaching metallic surface) and to minimize *parasitic* capacitance associated with wiring to and from the active elements. For these reasons, the recent trend is to use local microprocessors specialized for capacitance measurement as part of an integrated sensing system (Sect. 28.4). An example is shown in Fig. 28.4. VIDEO 15 actually shows results taken with the sensor depicted in Fig. 28.4.

Piezoresistive Pressure Sensing Arrays. Many researchers have produced tactile sensor arrays that are piezoresistive. In most cases, these sensors utilize a conductive rubber that is bulk molded or a piezoresistive ink that is patterned via screen printing or stamping. Each of these approaches employs a conductive additive (typically carbon black or silver) to create its conductive/piezoresistive behavior. As a more flexible and durable alternative, some researchers have developed fabric-based piezoresistive sensors, discussed separately below.

Russell [28.27] presented one of the first molded conductive rubber tactile sensor arrays composed of conductive rubber column and row electrodes with piezoresistive junctions. However, this sensor exhibited significant drift and hysteresis, which fueled research to minimize these effects through proper selection of molding material [28.8]. These issues were never completely solved due to the hysteretic nature of elastomers, but this sensing approach remains attractive due to its ease of manufacturing. Hence, it has continued to find applications, for example, in the appendages of humanoid robots where extreme accuracy is not required [28.104]. Significant improvements in dynamic range and robustness are also possible using a treated elastomer that exploits a quantum tunneling effect [28.105], and commercial versions are now available [28.106].

A number of researchers and companies have developed tactile sensors that utilize conductive (piezoresistive) ink, generally referred to as FSRs (force sensitive resistors). This is by far the most common and economical means to incorporate tactile sensing via off-the-shelf sensors. However, to make highly integrated, dense sensor arrays, custom fabrication is necessary. Examples of such sensors include [28.9, 29]. To take this basic concept a step further, *Someya* [28.107] has produced robotic skin that employs patterned organic semiconductors for local amplification of the piezoresistive sensor array, printed on flexible polyimide film. Although fabricated on a flexible substrate, these sensor arrays are somewhat susceptible to bending fatigue.

Piezoresistive fabrics have been developed to address fatigue and fragility issues found in tactile arrays. Examples of these sensors are presented in [28.10–12, 108] and are utilized in applications such as the arms or legs of humanoid robots. Because this technology has the potential to replace ordinary cloth, it is a promising technology for applications in wearable computing or even smart clothing. A different solution to the problem of making a sensor that will work on joints and locations with extensive flexing is to employ fine channels of liquid metal in a stretchy elastomer [28.109].

One final design that does not fall under the above fabrication categories is a sensor designed by *Kageyama* et al. [28.110] that utilizes a piezoresistive conductive gel pressure array along with a multi-level contact switch array via variable contact resistance within sensor layers that they developed for use in humanoid robots.

MEMS arrays. MEMS technology is attractive for producing dense sensor arrays with integrated packaging, signal processing and communications electronics. Early devices were produced in silicon through standard silicon micro-machining techniques, allowing high spatial resolution and dedicated hardware for multi-

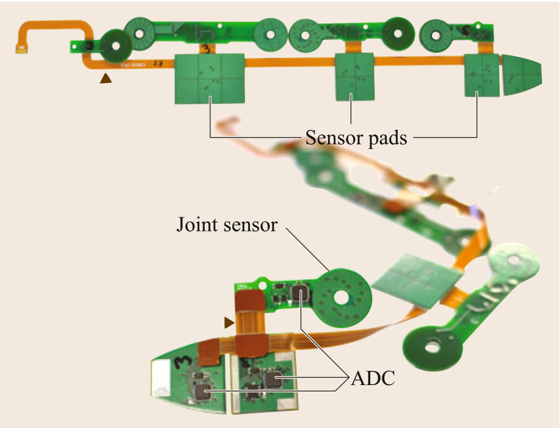


Fig. 28.4 Capacitive touch and joint angle sensors on a flexible circuit for incorporation in a robotic hand, sharing the same microprocessors for signal processing and communication (after [28.103])

plexing, etc. [28.111, 112]. However, such silicon-only devices can be brittle and difficult to integrate into a robust, compliant skin. More recent efforts have addressed these problems by using combinations of semiconductors and other materials, including organic semiconductors [28.18, 19, 52, 113, 114].

Returning to the idea of using silicon load cells for tactile sensing, *Valdastri* et al. [28.115] developed a miniature MEMS silicon-based three-axis load cell that resembles a joystick and is appropriate for embedding within an elastomeric skin for detecting shear and normal stresses (Fig. 28.5) [28.93]. Other recent efforts include flexible arrays with high spatial resolution using capacitive or piezoresistive technology [28.20, 116].

Skin Deflection Sensing

Brocket [28.117] was one of the first to propose the idea of using deformable membranes as robot fingertips. As noted by *Shimoga* and *Goldenberg* [28.118], there are several advantages to using deformable fingertips over more rigid robot fingertips, which include: 1) improved grasp stability, 2) reduced shock, and 3) reduced fatigue for embedded sensor elements. Other early work includes a deformable fingertip with skin covering polyurethane foam and instrumented with elastomeric strain gages [28.27].

Nowlin [28.25] used Bayesian algorithms to improve data interpretation of a deformable tactile sensor that used magnetic field sensing. A 4×4 array of magnets were supported above paired hall-effect sensors off a rigid base by individual fluid filled balloons. Hall-effect sensors measure the strength of the local magnetic field, which should increase with proximity to the magnets; however, this is complicated by neighboring magnets in the array. Hence, noisy data were combined using Bayesian algorithms to predict membrane deformation for a deformable fingertip.

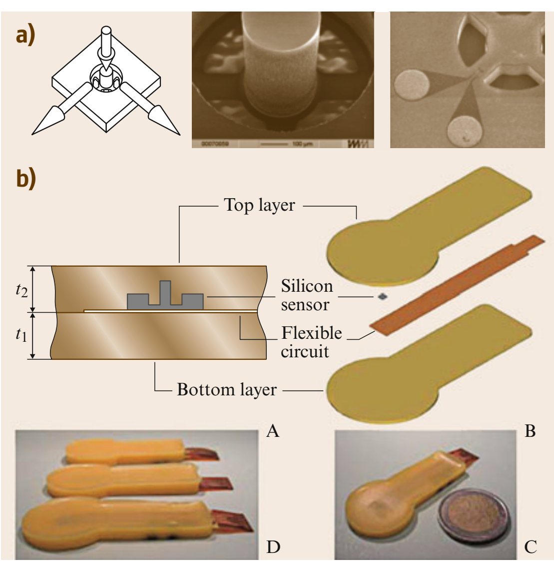


Fig. 28.5 **(a)** Scanning electron microscope (SEM) micrographs of a MEMS 3-axis tactile force sensor. **(b)** MEMS force sensor wirebonded to a flex-circuit and embedded within a silicone rubber skin (after [28.115])

Later, *Russell* and *Parkinson* [28.26] developed an impedance tomographic tactile sensor, capable of measure skin deformation over an 8×5 array. This sensor was constructed with of neoprene rubber and filled with distilled water, similar to the more recent BioTac sensor [28.24]. Row and column electrodes were made from copper and conductive rubber for the rigid substrate and neoprene skin, respectively. Like the capacitive tactile sensors described above, this sensor utilized multiplexing electronics to reduce the number of electrical interconnects. Square waveform driver electronics are used to estimate the resistance of a column of water formed between row and column elements providing a signal that is proportional to the current skin height.

Ferrier and *Brocket* [28.23] implemented a tactile sensor which used optical tracking in combination with models of the skin to predict sensor fingertip deformations. The fingertip sensor consists of a tiny CCD camera focused on a 7×7 array of dots marked on the inside of a gel-filled silicone membrane. An algorithm is used to construct a 13×13 grid over the array of dots. This algorithm uses a combination of the position that is sensed by the CCD camera, which provides the location along a line radially outward from the focal point, in combination with a mechanical model used to solve for the radial distance from the camera focal point, based on energy minimization.

A more recent example of a shape sensing array is the commercial Syntouch BioTac that grew out of research on a multimodal fingertip tactile sensor [28.24]. In this design, measuring the changes in resistance between terminals in a water-filled skin provides an estimate of the skin deformation.

Other Array Tactile Array Sensors

While less common than capacitive or piezoresistive sensors, optical tactile sensors have consistently been attractive for their immunity to electromagnetic interference. The basic approaches include designs that use a small camera to measure skin deformations and arrays of optical emitters and detectors. Optical fibers can also be used to separate the transducer from the contact site [28.42, 119].

An interesting tactile sensor uses vision to track an array of spherical markers embedded in a transparent elastomer to infer the stress state of the skin material due to applied forces [28.21]. This sensor is currently being commercialized under the tradename GelForce.

Miniaturization of optical components has also made it possible to construct a tactile array of surface-mounted optical devices. In a physically robust design that can be adapted for shear and normal sensing, emitters and detector pairs are covered by a thin translucent layer of silicone rubber followed by an opaque outer layer. As the silicone skin is depressed, there is a variation in the amount of light reflected from the emitter to the detector [28.22, 120].

The concept of reflection off the underside of a compliant skin has also been used with acoustic or ultrasonic sensors. *Shinoda* et al. [28.121] present a sensor that looks at the change in reflected accoustic energy from a resonator chamber near the surface of the skin, with application to friction measurement [28.122]. *Ando* et al. [28.123] present a more sophisticated ultrasound sensor that achieves 6-DOF (degree of freedom) displacement sensing via paired plate elements that utilize 4 ultrasound transducers per plate.

Multimodal Arrays

Human sensing is inherently multi-modal, with combinations of fast- and slow-acting mechanoreceptors as well as specialized thermal and pain receptors. In an analogous approach, a number of researchers have developed multi-modal tactile sensing suites that combine mechanical and thermal sensing [28.24, 49, 52, 124, 125]. As noted earlier, other work has combined static and dynamic sensing [28.24, 29, 32, 46, 92, 93, 126].

28.3 Tactile Information Processing

In discussing the processing of tactile information, we return first to the three main uses depicted in Fig. 28.1. For manipulation, we require, foremost, information about contact locations and forces so that we can grasp objects securely and impart desired forces and motions to them. For exploration, we are concerned with obtaining and integrating information about the object, including the local geometry, hardness, friction, texture, thermal conductivity, etc. For response, we are concerned especially with the detection of events, such as contacts produced by an external agent, and in assessing their types and magnitudes. The uses of information are often coupled. For example, we manipulate objects in order to explore them, and we use the information obtained through object exploration to improve our ability to control forces and motions in manipulation. Recognizing contact events is also important for manipulation and exploration, as it is for response.

28.3.1 Tactile Information Flow: Means and Ends of Tactile Sensing

Figure 28.6 summarizes the general flow of information from each type of sensor reviewed in the previous section through primary sensed quantities to information provided for manipulation, exploration and response. A useful thought exercise is to consider exactly what information we use to perform a task such as turning a pen end-over-end between the fingers. We can easily perform this task with our eyes closed. What information are we using? We need to track the position and orientation of the pen and to monitor the forces that we impose on it to maintain stable manipulation. In other words, we need to know the *configuration* of our grasp, the *locations and movements of contacts* over the surfaces of our fingers, the *magnitudes of grasp forces* and the *contact conditions* with respect to friction limits, etc. The same requirements apply for robots and are provided by the information flow in Fig. 28.6.

At the upper left corner of the figure, joint angles, combined with the forward kinematic model of the manipulator and knowledge of external link geometries, establish the positions and orientations of coordinate frames embedded in the fingertips. This information is needed to integrate local information about object shape, surface normal orientation, etc. so that the overall geometry and pose of the object can be determined.

Actuator effort sensors provide information about the resultant forces, using the Jacobian transpose: $\mathbf{J}^{\mathrm{T}}\boldsymbol{f} = \boldsymbol{\tau}$, where $\boldsymbol{f}$ is an $n \times 1$ vector of external forces and moments taken with respect to a coordinate frame embedded in the appendage. $\mathbf{J}^{\mathrm{T}}$ is the Jacobian transpose, mapping external forces and moments to joint torques, and $\boldsymbol{\tau}$ is an $m \times 1$ vector of joint torques for a serial kinematic chain with m degrees of freedom. We require that the k-th column of $\mathbf{J}^{\mathrm{T}}$ have elements that are relatively large compared to the overall condition number of $\mathbf{J}$ to provide an accurate measurement of the k-th element of $\boldsymbol{f}$. *Eberman* and *Salisbury* [28.127] show that it is possible to measure contact force and location using only joint torque measurements if the manipulator has clean dynamics.

Alternatively, we can use a multi-axis force–torque sensor in the fingers, as shown in Fig. 28.3, or robot wrist to obtain contact forces. This approach has the advantage of providing dynamic force signals with

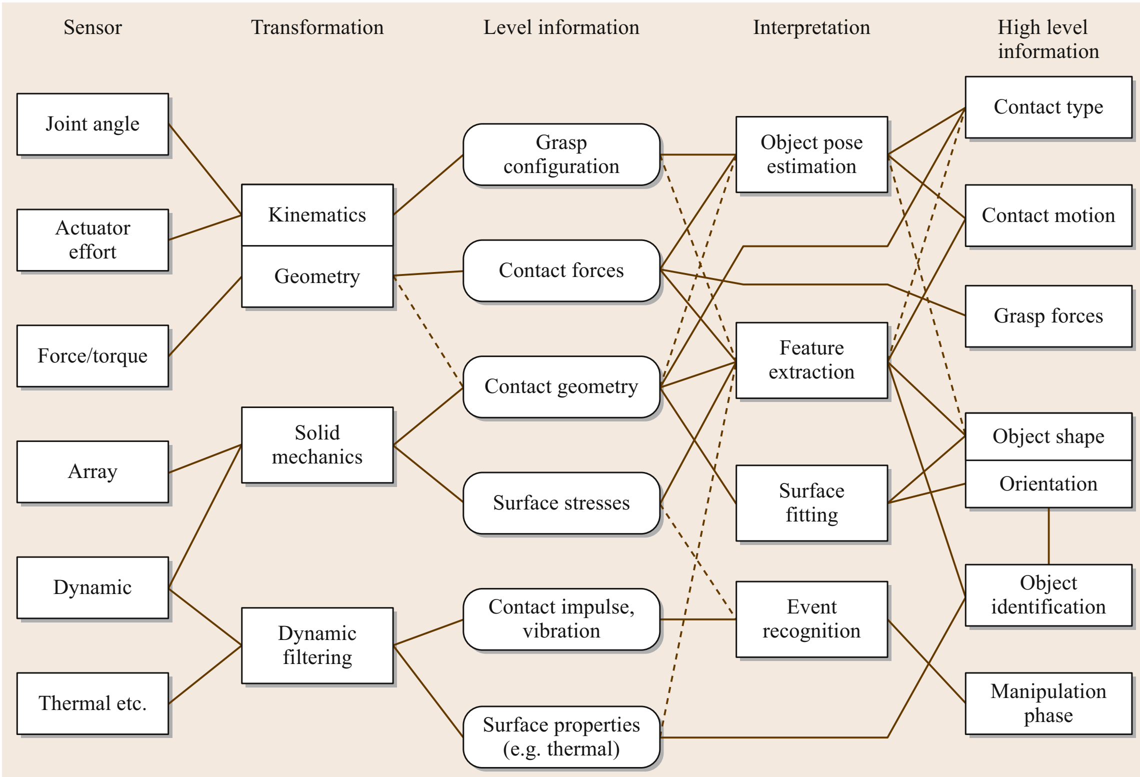


Fig. 28.6 Force and tactile sensor information flow and signal processing

a higher signal/noise ratio because they are not masked by the inertias of the robot arm or fingers and their transmissions. If the geometry of the fingertip is known, one can use *intrinsic tactile sensing* [28.65, 128] to compute the contact location as well as the contact force by examining ratios of resultant forces and torques at the sensor.

When the contacts are small compared to the fingertips (so that a point-contact approximation applies) and the fingertips are convex shapes, the contact location is easily computed. Fig. 28.7 shows a contact force $\boldsymbol{f}$, contacting the fingertip surface at a location $\boldsymbol{r}$. A force–torque sensor such as that in Fig. 28.2 measures the moment, $\boldsymbol{\tau} = \boldsymbol{r} \times \boldsymbol{f}$, with respect to the origin. If we consider the lever arm $\boldsymbol{h}$, perpendicular to the line of action of $\boldsymbol{f}$, then $\boldsymbol{h}/h = \boldsymbol{f}/f \times \boldsymbol{\tau}/\tau$, where $h = \tau/f$ is the magnitude of $\boldsymbol{h}$. We can then write that $\boldsymbol{r} = \boldsymbol{h} - \alpha\boldsymbol{f}$, where α is a constant obtained by solving for the intersection of the line of action and the fingertip surface. For a convex fingertip, there will be two such points, of which only one corresponds to a positive (inward) contact force.

From the contact location one can deduce the local contact normal and contact kinematic type from a small number of force measurements. *Bicchi* presents algorithms for extending these methods to soft fingers [28.128]. *Brock* and *Chiu* [28.66] describe the use of force sensors for the perception of object shape using this approach and for measuring the mass and center of mass of a grasped object.

For precision tasks involving small objects or small forces and motions, cutaneous sensors provide the most sensitive measurements. In general, as task require-

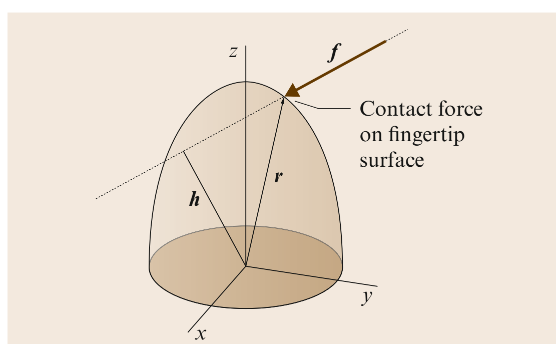


Fig. 28.7 Intrinsic tactile sensing: a contact produces a unique line of action and moment about the origin of a coordinate system in the fingertip. The contact location can be obtained by solving for the intersection of the line of action and the fingertip surface

ments get smaller, the sensor must be located closer to the contact so that the compliance and inertia of the intervening parts of the manipulator do not interfere with the measurement. *Dario* [28.129] suggests that finger tip force sensors are useful for forces of 0.1–10.0 N while array sensors can measure distributed forces of 0.01–1.0 N. *Son* et al. [28.74] find that intrinsic tactile sensing and array sensors can both provide accurate (within 1 mm) estimates of contact location; however, the intrinsic tactile sensing method is inherently sensitive to the accuracy of the force–torque sensor calibration and can produce transient errors due to unmodeled dynamic forces.

Proceeding down the left side of Fig. 28.6 we come to the large category of cutaneous array sensors. The interpretation of information from array sensors depends initially on the transducer type. For arrays of binary contact or proximity sensors, interpretation amounts mainly to establishing the location and general shape of the contact area. Techniques common to binary vision can be used to obtain sub-pixel resolution and to identify contact features. This information, in combination with measurements of the grasp forces from actuator effort or force–torque sensors, is sufficient for basic manipulation tasks [28.69].

28.3.2 Solid Mechanics and Deconvolution

A basic problem associated with tactile array sensors is to reconstruct what is happening at the surface of the skin from a finite set of measurements obtained beneath the surface. Typically we are interested in determining pressure and perhaps shear stress distributions associated with contacts on the skin. In other cases, as when the fingertips consist of a gel or soft foam covered by a thin membrane so that the pressure is nearly constant, the local geometry of the contact is of interest.

In the following example we consider the case of an array of elements located at a depth d below the surface of an elastomeric skin. A contact has resulted in a pressure distribution over the region of interest. We establish a coordinate system with z pointing in the inward normal direction and, for simplicity, we examine a one-dimensional loading case, $p(y)$, in which the pressure distribution is unchanging in the x direction. We further assume that the extent of the skin in the x direction is large compared to the skin thickness so that strains in the x direction are inhibited, leading to a plane strain elasticity problem. We assume that the skin is a homogenous, isotropic material and the strains are small enough that linear elasticity theory can be applied. Of course, none of these assumptions is entirely valid in practical cases; however, the results do agree qualitatively with the measurements obtained with actual robot fingers and tactile arrays. A thorough discussion of the general approach and of the accuracy of the linear elastic models can be found in [28.91, 96, 99, 130, 131].

Figure 28.8 illustrates the case of two line loads, or knife edges, pressed against the surface of the skin (akin to a planar version of the two-point discrimination test for human tactile acuity). The solution for a single line load, or impulse response, was derived by Boussinesq in 1885. For the case of plane strain the principal stresses in the (y,z) plane from a normal unit impulse can be expressed in cartesian coordinates as [28.132]

$$\sigma_z(y,z) = \left(\frac{-2}{\pi z}\right)\frac{1}{[1+(y/z)^2]^2}\,, \tag{28.1}$$

$$\sigma_y(y,z) = \left(\frac{-2}{\pi z}\right)\frac{(y/z)^2}{[1+(y/z)^2]^2}\,, \tag{28.2}$$

$$\sigma_x(y,z) = \nu(\sigma_y+\sigma_z)\,, \tag{28.3}$$

where ν is Poisson's ratio for the material (typically 0.5 for elastomeric materials).

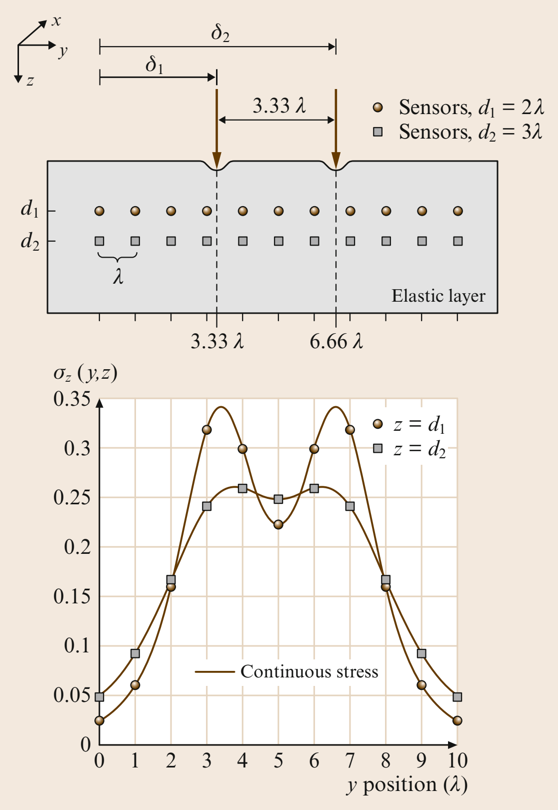


Fig. 28.8 Plane strain stress response for two (unit magnitude) line loads. Note the *blurring* that occurs with greater depth

For two such line loads located at distances δ_1 and δ_2 from the origin, the solution can be obtained by superposition

$$\sigma_z(y,z) = \left(\frac{-2}{\pi z}\right)\left\{\frac{1}{\left[1+\left(\frac{y-\delta_1}{z}\right)^2\right]^2} + \frac{1}{\left[1+\left(\frac{y-\delta_2}{z}\right)^2\right]^2}\right\}, \tag{28.4}$$

$$\sigma_y(y,z) = \left(\frac{-2}{\pi z}\right)\left\{\frac{\left(\frac{y-\delta_1}{z}\right)^2}{\left[1+\left\{\frac{y-\delta_1}{z}\right\}^2\right]^2} + \frac{\left(\frac{y-\delta_2}{z}\right)^2}{\left[1+\left\{\frac{y-\delta_2}{z}\right\}^2\right]^2}\right\}. \tag{28.5}$$

For more general pressure distributions the stresses can be found by convolution of the pressure distribution, $p(y)$, and the impulse response $G_i(y,z)$

$$\sigma_i = \int_{\tau=-\infty}^{\tau=y} [p(\tau)\mathrm{d}\tau] G_i(y-\tau, z)\,. \tag{28.6}$$

Also plotted in Fig. 28.8 are curves corresponding to the vertical stress components, σ_z, at two different depths $d_1 = 2\lambda$ and $d_2 = 3\lambda$, where λ is the sensor spacing. As we go deeper beneath the skin, the stresses become smoothed or blurred, and the ability to distinguish between closely spaced impulses diminishes. However, the blurring of concentrated pressure distributions can also provide an advantage when we have a limited number of sensors because the stresses and strains spread over a larger area and are more likely to affect at least one sensor. The elastic skin also provides a kind of automatic *edge enhancement* because stresses are high at the transitions between loaded and unloaded regions of the skin.

In most cases, for example in the case of capacitive or magnetic sensors, the sensing elements will measure strains or local deformations of the skin material in the vertical direction. In a few cases, such as pieces of piezoelectric film embedded in an elastomeric skin [28.91], the sensors are sufficiently stiff compared to the surrounding material that they can be considered to measure stresses directly.

For the case of elastic plane strain, the strains are related to the stresses by [28.133]

$$\epsilon_y = \frac{1}{E}\left[\sigma_y - \nu(\sigma_x + \sigma_z)\right]\,, \tag{28.7}$$

$$\epsilon_z = \frac{1}{E}\left[\sigma_z - \nu(\sigma_x + \sigma_y)\right]\,, \tag{28.8}$$

where E is the Young's modulus and ν is the Poisson's ratio, which we assume is 0.5 for an elastomeric skin.

Figure 28.9 shows the typical measurements that may be obtained from a row of sensing elements from the two line loads applied in Fig. 28.8. Each bar corresponds to the strain, ϵ_{zi} measured by a corresponding element and computed using (28.8), with stresses obtained from (28.3)–(28.5).

The problem at this point is to produce a best estimate of the surface pressure distribution, $p(y)$, from this finite set of subsurface strain measurements. The problem is a classic example of estimating a signal from a sparse set of remote measurements. One approach to this process is based on deconvolution techniques [28.91, 96, 99]. The measured signal from the sensors $\boldsymbol{\epsilon}_z$ is convolved with the inverse of the impulse strain response $H(y)$ to find an estimate of the surface pressure that produced the signals. The inversion tends to amplify high frequency noise, and the inverse filter bandwidth must be limited according to the spatial density of the sensors and their depth below surface.

Another approach [28.21, 130] is to assume that the surface pressure distribution can be approximated by a finite set of impulses $\boldsymbol{p} = [p_1, p_2 \dots p_n]^t$. The sensor readings form a vector, $\boldsymbol{\epsilon} = [\epsilon_1, \epsilon_2 \dots \epsilon_m]^t$, where $m > n$ for the bandwidth limitations discussed above. The strain response can then be written as a matrix

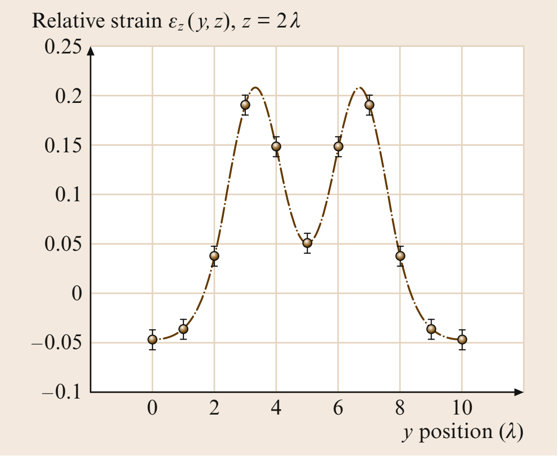


Fig. 28.9 Measured strain with assumed 10% noise

equation

$$\boldsymbol{\epsilon} = \mathbf{H}\boldsymbol{p} . \quad (28.9)$$

Each element of $\mathbf{H}$ is computed using (28.8) with σ_z and σ_y computed using equations similar to (28.4) and (28.5) and with σ_x from (28.3). The estimated discrete pressure distribution is then found by taking the pseudoinverse of $\mathbf{H}$

$$\hat{p} = \mathbf{H}^{+}\boldsymbol{\epsilon} . \quad (28.10)$$

Using the strain measurements from Fig. 28.9, at a depth $d = 2\lambda$, the estimated pressure distribution using the pseudoinverse method is seen in Fig. 28.10. In this example, because the assumed set of seven impulses matches fortuitously with the actual loading, the reconstruction is fairly accurate despite the assumed noise.

An alternative approach to constructing soft robot finger tips is to enclose a compliant medium such as foam rubber or fluid in a thin elastic membrane [28.25, 27, 117, 134–137]. Some of the tactile array sensors developed for these fingers are able to measure directly the shape of the membrane, so that a physical model is not needed for interpretation of the signal [28.25]. Another sensing scheme uses an array of magnetic sensors at the center of the finger to measure the changes in the magnetic field generated by deformations of the magnet-loaded membrane [28.137]. A statistical algorithm has been developed that can robustly determine the membrane shape from the sensor signals [28.25]. However, a mechanical model is still required to find the pressure distribution across the contact from the shape information provided by all of these sensors.

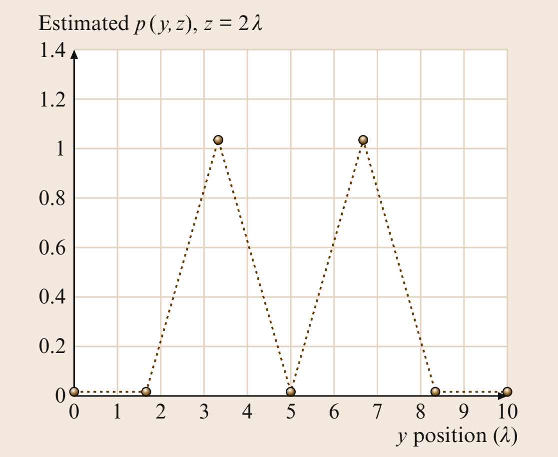


Fig. 28.10 Estimated surface pressure distribution using pseudoinverse method for 11 sensors and 7 assumed impulses

28.3.3 Curvature and Shape Information

Another alternative to measuring subsurface strains or deflections is to measure directly the local curvature at each element of an array of sensors. The curvature information can be applied directly toward identifying contact type and centroid location or integrated to obtain the local shape of the contact [28.28, 138].

Returning to Fig. 28.6, once the local contact shape or geometry has been established, the next steps typically include feature identification (e.g., identifying corners or ridges on an object) and determining the overall shape and pose of the object in the hand.

Often the object shape is at least partially known a priori in which case a variety of surface or data fitting methods can be used. For example, *Fearing* [28.139] developed a method for calculation of the radius of curvature and orientation of a generalized cylinders from tactile array data and [28.140] developed a neural network that performs a similar calculation. Other schemes use contact locations, surface normals and contact forces to determine information about object shape and orientation with respect to the hand [28.141–144].

Allen [28.145] uses several different primitive representations for object shape attributes based on the particular exploratory procedure used to sense the object. Object volume and approximate shape are perceived with enclosure grasping, and the resulting shape is modeled using superquadric surfaces. Similarly, measurement of the lateral extent of object faces leads to a face-edge-vertex model and contour following to a generalized cylinder representation.

The question of what constitutes an appropriate set of features is not well understood, although it clearly depends on the intended application. *Ellis* [28.146] considers appropriate feature sets and methodologies for acquiring the needed data. *Lederman* and *Browse* [28.147] suggest that surface roughness, surface curvature, and oriented edges are used in human haptic perception.

28.3.4 Object and Surface Identification

The most common application of touch information has been in object recognition and classification. In object recognition the goal is to identify one object from a set of known objects using information derived from touch. In classification the goal is to categorize objects according to preselected sensed properties. These systems are usually based on geometric information derived from tactile array or force sensors, although some approaches use additional information (e.g., compliance, texture, thermal properties and the kinematic pose of the hand) [28.148–154].

28.3.5 Active Sensing Strategies

Because touch provides only local information, movement is an integral part of touch sensing for recognition and exploration. A review of tactile sensing focusing on exploration and manipulation is found in [28.2]. Several researchers have developed strategies for scheduling sensor movements so that each additional observation decreases the number of objects which are consistent with prior observations. This is sometimes described as a *hypothesize and test* approach. Early examples include [28.141, 155–157].

Klatzky et al. [28.149] have suggested that robotics systems can employ the same exploratory procedures used by humans in haptic exploration. These procedures prescribe the finger motions needed for tasks such as tracing object contours, measuring compliance, and determining the lateral extent of object surfaces. Early work on exploratory tactile sensing includes [28.145, 158, 159]. More recent examples include [28.32, 160, 161].

Edge tracking and surface following strategies have received particular attention. Early examples include [28.162–166]; a more recent example is found in [28.167].

28.3.6 Dynamic Sensing and Event Detection

For dynamic tactile sensors used to detect such events as gentle contacts or slippage between the fingertips and an object, the main challenge is to reliably detect the event in question without false positives. The dynamic tactile sensors that produce large signals in response to contact events are also prone to producing large signals in response to vibrations from the robot drive train and to rapid accelerations of the robot hand. Solutions for more robustly detecting contact events include comparing the signals from dynamic tactile sensors at and away from the contact regions and statistical pattern recognition methods to identify the *signature* of true contact events. Early examples include [28.86, 127, 168]. More recent examples have taken advantage of the much greater realtime processing capability that is now available for signal processing and event classification [28.32, 161, 169, 170].

28.3.7 Integration of Thermal and Other Sensors

Sensors such as thermal contact sensors are rarely used in isolation; their signals are generally integrated with those from tactile arrays and other sensors to produce additional information for identifying objects. Examples of integrated thermal and mechanical sensors for surface characterization include [28.24, 52, 171].

28.4 Integration Challenges

A critical problem that we have not yet addressed is the difficulty of connecting to a large and diverse array of tactile sensors. In 1987 *Jacobsen* et al. [28.172] cited the routing of wires as perhaps the most difficult problem in dexterous hand design and, to a large extent, this remains true today. However, some solutions to this problem have been presented in recent years using wireless sensor arrays or digital busses for power and signal connections.

In early work, *Shinoda* and *Oasa* [28.173] embedded tiny wireless sensing elements in an elastic skin that uses an inductive base coil to provide power and signal transmission. *Hakozaki* and *Shinoda* [28.174] embed tactile sensor chips between 2 layers of conductive rubber provide power and serial communication. In other work, [28.18, 20] produce large scale printed arrays with built-in multiplexing and communications.

In a different approach, *Yamada* et al. [28.168] use wireless sensor chips and light transmitted through a transparent elastomer both for power and to communicate to a power-receiver chip. *Ascari* et al. [28.175] propose a communications scheme with all information transmitted along optical fibers.

In recent years, the proliferation of microprocessors that can perform local signal conditioning, multiplexing and digital communications has been particularly helpful.These devices, adapted from touch-screens, are small enough to be located at the fingertips of a hand. One solution is to modify the barometric pressure sensing chips common in cell phones, converting them into pressure sensing elements [28.95, 176]. Another is to use processors adapted for capacitive touch screens [28.94, 103]. Still another involves arrays of optical tactile devices [28.22].

28.5 Conclusions and Future Developments

In comparison to computer vision, tactile sensing always seems to be *a few years away* from widespread adoption. As explained in the introduction to this chapter, the reasons include physical problems (placement and robustness of sensors, wiring challenges) and the diversity of sensor types for detecting forces, pressures, local geometries, vibrations, etc. As we have seen, the transduction and interpretation methods are typically different for each of these tactile quantities. However, there are some basic issues that apply to tactile sensing in general. For example, sensors are generally located within or beneath a compliant skin, which affects the quantities that they sense in comparison to pressures, stresses, thermal gradients or displacements applied to the skin surface.

When choosing tactile sensors for a robot arm or hand, it is effective to begin with a consideration of which tactile quantities are most desired and for what purpose. For example, if the main concern is to obtain accurate measurements of loads or contact forces at sufficient data rates for force servoing, then intrinsic tactile sensing may make the most sense. If manipulating objects with soft contacts and with sliding or rolling, curved array sensors for measuring pressure distributions, or perhaps local skin deflections, may be desirable. If exploring objects to learn about their texture and material composition, dynamic tactile sensors and thermal sensors may be effective.

In an ideal world, one would incorporate all these tactile sensors in a robotic end-effector without regard to cost, signal processing or wiring complexity. Fortunately, the cost and size of transducers suitable for tactile sensing are steadily dropping and the ability to perform localized processing is improving with surface-mounted devices on flexible circuits. In the near future it will be increasingly possible to fabricate dense arrays of transducers in-situ on contoured surfaces, using material deposition and laser machining techniques. In this way, robots may finally start to approach the tactile sensitivity and responsiveness of animals.

Video-References

VIDEO 14 The effect of twice dropping, and then gently placing, a two gram weight on a small capacitive tactile array
available from http://handbookofrobotics.org/view-chapter/28/videodetails/14

VIDEO 15 Capacitive tactile sensing
available from http://handbookofrobotics.org/view-chapter/28/videodetails/15

References

28.1 M.I. Tiwana, S.J. Redmond, N.H. Lovell: A review of tactile sensing technologies with applications in biomedical engineering, Sens. Actuators A Phys. **179**, 17–31 (2012)

28.2 H. Yousef, M. Boukallel, K. Althoefer: Tactile sensing for dexterous in-hand manipulation in robotics – A review, Sens. Actuators A Phys. **167**(2), 171–187 (2011)

28.3 R.S. Dahiya, G. Metta, M. Valle, G. Sandini: Tactile sensing – From humans to humanoids, IEEE Trans. Robotics **26**(1), 1–20 (2010)

28.4 C. Lucarotti, C.M. Oddo, N. Vitiello, M.C. Carrozza: Synthetic and bio-artificial tactile sensing: A review, Sensors **13**(2), 1435–1466 (2013)

28.5 M.H. Lee: Tactile sensing: new directions, new challenges, Int. J. Robotic Res. **19**(7), 636–643 (2000)

28.6 M.H. Lee, H.R. Nicholls: Tactile sensing for mechatronics-a state of the art survey, Mechatronics **9**(1), 1–31 (1999)

28.7 L.D. Harmon: Automated tactile sensing, Int. J. Robotics Res. **1**(2), 3–32 (1982)

28.8 J.-P. Uldry, R.A. Russell: Developing conductive elastomers for applications in robotic tactile sensing, Adv. Robotics **6**(2), 255–271 (1992)

28.9 T.V. Papakostas, J. Lima, M. Lowe: A large area force sensor for smart skin applications, Proc. IEEE Sens., Vol. 2 (2002) pp. 1620–1624

28.10 M. Shimojo, A. Namiki, M. Ishikawa, R. Makino, K. Mabuchi: A tactile sensor sheet using pressure conductive rubber with electrical-wires stitched method, IEEE Sens. J. **4**(5), 589–596 (2004)

28.11 D. De Rossi, A. Della Santa, A. Mazzoldi: Dressware: wearable piezo- and thermoresistive fabrics for ergonomics and rehabilitation, Proc. 19th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc., Vol. 5 (1997) pp. 1880–1883

28.12 A. Tognetti, F. Lorussi, M. Tesconi, D. De Rossi: Strain sensing fabric characterization, Proc. IEEE Sens., Vol. 1 (2004) pp. 527–530

28.13 R.S. Fearing, T.O. Binford: Using a cylindrical tactile sensor for determining curvature, IEEE Trans. Robotics Autom. **7**(6), 806–817 (1991)

28.14 Pressure Profile Systems: http://www.pressureprofile.com/
28.15 H.-K. Lee, S.-I. Chang, E. Yoon: A flexible polymer tactile sensor: Fabrication and modular expandability for large area deployment, J. Microelectromechanical Syst. **15**(6), 1681–1686 (2006)
28.16 T. Hoshi, H. Shinoda: A sensitive skin based on touch-area-evaluating tactile elements, Proc. 14th Symp. Haptic Interfaces Virtual Env. Teleoperator Syst. (2006) pp. 89–94
28.17 P. Maiolino, M. Maggiali, G. Cannata, G. Metta, L. Natale: A flexible and robust large scale capacitive tactile system for robots, IEEE Sens. J. **13**(10), 3910–3917 (2013)
28.18 T. Sekitani, M. Takamiya, Y. Noguchi, S. Nakano, Y. Kato, T. Sakurai, T. Someya: A large-area wireless power-transmission sheet using printed organic transistors and plastic MEMS switches, Nat. Mater. **6**(6), 413–417 (2007)
28.19 R.S. Dahiya, D. Cattin, A. Adami, C. Collini, L. Barboni, M. Valle, L. Lorenzelli, R. Oboe, G. Metta, F. Brunetti: Towards tactile sensing system on chip for robotic applications, IEEE Sens. J. **11**(12), 3216–3226 (2011)
28.20 K. Takei, T. Takahashi, J.C. Ho, H. Ko, A.G. Gillies, P.W. Leu, R.S. Fearing, A. Javey: Nanowire active-matrix circuitry for low-voltage macroscale artificial skin, Nat. Mater. **9**(10), 821–826 (2010)
28.21 K. Kamiyama, H. Kajimoto, N. Kawakami, S. Tachi: Evaluation of a vision-based tactile sensor, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 2 (2004) pp. 1542–1547
28.22 M. Quigley, C. Salisbury, A.Y. Ng, J.K. Salisbury: Mechatronic design of an integrated robotic hand, Int. J. Robobotics Res. **33**(5), 706–720 (2014)
28.23 N.J. Ferrier, R.W. Brockett: Reconstructing the shape of a deformable membrane from image data, Int. J. Robotics Res. **19**(9), 795–816 (2000)
28.24 C.H. Lin, T.W. Erickson, J.A. Fishel, N. Wettels, G.E. Loeb: Signal processing and fabrication of a biomimetic tactile sensor array with thermal, force and microvibration modalities, Proc. IEEE Int. Conf. Robotics Biomim. (ROBIO) (2009) pp. 129–134
28.25 W.C. Nowlin: Experimental results on Bayesian algorithms for interpreting compliant tactile sensing data, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 1 (1991) pp. 378–383
28.26 R.A. Russell, S. Parkinson: Sensing surface shape by touch, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 1 (1993) pp. 423–428
28.27 R.A. Russell: Compliant-skin tactile sensor, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1987) pp. 1645–1648
28.28 W.R. Provancher, M.R. Cutkosky: Sensing local geometry for dexterous manipulation, Proc. Intl. Symp. Exp. Robotics (2002) pp. 507–516
28.29 P. Dario, R. Lazzarini, R. Magni, S.R. Oh: An integrated miniature fingertip sensor, Proc. 7th Int. Symp. Micro Mach. Hum. Sci. (1996) pp. 91–97
28.30 R.D. Howe, M.R. Cutkosky: Dynamic tactile sensing: perception of fine surface features with stress rate sensing, IEEE Trans. Robotics Autom. **9**(2), 140–151 (1993)
28.31 R.D. Howe, M.R. Cutkosky: Sensing skin acceleration for texture and slip perception, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 1 (1989) pp. 145–150
28.32 J.M. Romano, K. Hsiao, G. Niemeyer, S. Chitta, K.J. Kuchenbecker: Human-inspired robotic grasp control with tactile sensing, IEEE Trans. Robotics **27**(6), 1067–1079 (2011)
28.33 J. Lee, S.N. Sponberg, O.Y. Loh, A.G. Lamperski, R.J. Full, N.J. Cowan: Templates and anchors for antenna-based wall following in cockroaches and robots, IEEE Trans. Robotics **24**(1), 130–143 (2008)
28.34 T.J. Prescott, M.J. Pearson, B. Mitchinson, J.C. Sullivan, A. Pipe: Whisking with robots: from rat vibrissae to biomimetic technology for active touch, IEEE Robotics Autom. Mag. **16**(3), 42–50 (2009)
28.35 R.A. Russell: Using tactile whiskers to measure surface contours, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1992) pp. 1295–1299
28.36 M. Kaneko, N. Kanayama, T. Tsuji: Active antenna for contact sensing, IEEE Trans. Robotics Autom. **14**(2), 278–291 (1998)
28.37 T.N. Clements, C.D. Rahn: Three-dimensional contact imaging with an actuated whisker, IEEE Trans. Robotics **22**(4), 844–848 (2006)
28.38 T.J. Prescott, M.J. Pearson, B. Mitchinson, J.C. Sullivan, A. Pipe: Tactile discrimination using active whisker sensors, IEEE Sens. J. **12**(2), 350–362 (2012)
28.39 J.M. Vranish, R.L. McConnell, S. Mahalingam: Capaciflector collision avoidance sensors for robots, Comput. Electr. Eng. **17**(3), 173–179 (1991)
28.40 E. Cheung, V. Lumelsky: A sensitive skin system for motion control of robot arm manipulators, Robotics Auton. Syst. **10**(1), 9–32 (1992)
28.41 D. Um, V. Lumelsky: Fault tolerance via component redundancy for a modularized sensitive skin, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1999) pp. 722–727
28.42 S. Walker, K. Loewke, M. Fischer, C. Liu, J.K. Salisbury: An optical fiber proximity sensor for haptic exploration, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (2007) pp. 473–478
28.43 P. Wei, L. Zhizeng: A design of miniature strong anti-jamming proximity sensor, Proc. Int. Conf. Comp. Sci. Electron. Eng. (ICCSEE) (2012) pp. 327–331
28.44 E. Guglielmelli, V. Genovese, P. Dario, G. Morana: Avoiding obstacles by using a proximity US/IR sensitive skin, IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS) (1993) pp. 2207–2214
28.45 D. Wegerif, D. Rosinski: Sensor based whole arm obstacle avoidance for kinematically redundant robots, Proc. SPIE – Int. Soc. Opt. Eng. **1828**, 417–426 (1992)
28.46 G. Buttazzo, P. Dario, R. Bajcsy: Finger based explorations, Proc. SPIE 0726, Intell. Robots Comput. Vis. V, ed. by D.P. Casadent (1986) pp. 338–345

28.47 D. Siegel, I. Garabieta, J. Hollerbach: An integrated tactile and thermal sensor, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1986) pp. 1286–1291
28.48 R.A. Russell: A thermal sensor array to provide tactile feedback for robots, Int. J. Robotics Res. **5**(3), 35–39 (1985)
28.49 F. Castelli: An integrated tactile-thermal robot sensor with capacitive tactile array, IEEE Trans. Ind. Appl. **38**(1), 85–90 (2002)
28.50 D.G. Caldwell, C. Gosney: Enhanced tactile feedback (Tele-taction) using a multi-functional sensory system, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) **1**, 955–960 (1993)
28.51 G.J. Monkman, P.M. Taylor: Thermal tactile sensing, IEEE Trans. Robotics Autom. **9**(3), 313–318 (1993)
28.52 J. Engel, J. Chen, X. Wang, Z. Fan, C. Liu, D. Jones: Technology development of integrated multi-modal and flexible tactile skin for robotics applications, Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS), Vol. 3 (2003) pp. 2359–2364
28.53 P. Bergveld: Development and application of chemical sensors in liquids. In: *Sensors and Sensory Systems for Advanced Robots*, NATO ASI Series, Vol. 43, ed. by P. Dario (Springer, Berlin, Heidelberg 1988) pp. 397–414
28.54 T. Nakamoto, A. Fukuda, T. Moriizumi: Perfume and flavor identification by odor sensing system using quartz-resonator sensor array and neural-network pattern recognition, Proc. 6th Int. Conf. Solid-State Sens. Actuators (TRANSDUCERS '91) (1991)
28.55 R.A. Russell: Survey of robotic applications for odor-sensing technology, Int. J. Robotics Res. **20**(2), 144–162 (2001)
28.56 A.J. Lilienthal, A. Loutfi, T. Duckett: Airborne chemical sensing with mobile robots, Sensors **6**(11), 1616–1678 (2006)
28.57 B.A. Auld, A.J. Bahr: A novel multifunction robot sensor, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1986) pp. 1791–1797
28.58 H. Clergeot, D. Placko, J.M. Detriche: Electrical proximity sensors. In: *Sensors and Sensory Systems for Advanced Robots*, NATO ASI Series, Vol. 43, ed. by P. Dario (Springer, Berlin, Heidelberg 1988) pp. 295–308
28.59 M. Kaneko, K. Tanie: Contact point detection for grasping of an unknown object using self-posture changeability (SPC), IEEE Trans. Robotics Autom., Vol. 10 (1994) pp. 355–367
28.60 A.M. Dollor, L.P. Jentoft, J.H. Cao, R.D. Howe: Contact sensing and grasping performance of compliant hands, Auton. Robots **28**(1), 65–75 (2010)
28.61 J.K. Salisbury: Appendix to kinematic and force analysis of articulated hands. In: *Robot Hands and the Mechanics of manipulation*, ed. by M.T. Mason, J.K. Salisbury (MIT Press, Cambridge 1985)
28.62 G. Palli, C. Melchiorri, G. Vassura, U. Scarcia, L. Moriello, G. Berselli, A. Cavallo, G. De Maria, C. Natale, S. Pirozzi, C. May, F. Ficuciello, B. Siciliano: The DEXMART hand: Mechatronic design and experimental evaluation of synergy-based control for human-like grasping, Int. J. Robotics Res. **33**(5), 799–824 (2014)
28.63 A. Pugh (Ed.): *Robot Sensors, Volume 2: Tactile and Non-Vision* (IFS Publ./Springer, New York 1986)
28.64 J.G. Webster: *Tactile Sensors for Robotics and Medicine* (Wiley, New York 1988)
28.65 J.K. Salisbury: Interpretation of contact geometries from force measurements. In: *Robotics Res. First Int. Symp*, ed. by M. Brady, R.P. Paul (MIT Press, Cambridge 1984)
28.66 D. Brock, S. Chiu: Environment perception of an articulated robot hand using contact sensors, ASME Winter Annu. Meet. Robotics Manuf. Automa., Vol. 15 (1985) pp. 89–96
28.67 J. Butterfass, M. Grebenstein, H. Liu, G. Hirzinger: DLR-Hand II: next generation of a dextrous robot hand, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 1 (2001) pp. 109–114
28.68 F.W. Sinden, R.A. Boie: A planar capacitive force sensor with six degrees of freedom, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1986) pp. 1806–1813
28.69 B.B. Edin, L. Beccai, L. Ascari, S. Roccella, J.J. Cabibihan, M.C. Carrozza: A bio-inspired approach for the design and characterization of a tactile sensory system for a cybernetic prosthetic hand, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (2006) pp. 1354–1358
28.70 Y.-L. Park, S.C. Ryu, R.J. Black, K.K. Chau, B. Moslehi, M.R. Cutkosky: Exoskeletal force-sensing end-effectors with embedded optical fiber-bragg-grating sensors, IEEE Trans. Robotics **25**(6), 1319–1331 (2009)
28.71 A. Bicchi: A criterion for optimal design of multiaxis force sensors, Robotics Auton. Syst. **10**(4), 269–286 (1992)
28.72 M. Uchiyama, E. Bayo, E. Palma-Villalon: A mathematical approach to the optimal structural design of a robot force sensor, Proc. USA-Japan Symp. Flexible Automation (1998) pp. 539–546
28.73 A. Bicchi, J.K. Salisbury, P. Dario: Augmentation of grasp robustness using intrinsic tactile sensing, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 1 (1989) pp. 302–307
28.74 J.S. Son, M.R. Cutkosky, R.D. Howe: Comparison of contact sensor localization abilities during manipulation, Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS), Vol. 2 (1995) pp. 96–103
28.75 R.S. Johansson, J.R. Flanagan: Coding and use of tactile signals from the fingertips in object manipulation tasks, Nat. Rev. Neurosci. **10**(5), 345–359 (2009)
28.76 M. Ueda: Tactile sensors for an industrial robot to detect a slip, Proc. 2nd Int. Symp. Ind. Robots (1972) pp. 63–70
28.77 R. Matsuda: Slip sensor of industrial robot and its application, Electric. Eng. Jap. **96**(5), 129–136 (1976)
28.78 J. Rebman, J.-E. Kallhammer: A Search for Precursors of Slip in Robotic Grasp, Intelligent Robots

and Computer Vision: Fifth in a Series, Cambridge, ed. by E. Casaent (1986) pp. 329–337
28.79 P. Dario, D. De Rossi: Tactile sensors and the gripping challenge, IEEE Spectrum **22**(8), 46–52 (1985)
28.80 R.W. Patterson, G.E. Nevill: The induced vibration touch sensor – A new dynamic touch sensing concept, Robotica **4**(01), 27–31 (1986)
28.81 M.R. Cutkosky, J. Ulmen: Dynamic Tactile Sensing. In: *The Human Hand as an Inspiration for Robot Hand Development*, Springer Tracts in Advanced Robotics 95, ed. by R. Balasubramanian, V.J. Santos (Springer, Cham 2014) pp. 389–403
28.82 D. Dornfeld, C. Handy: Slip detection using acoustic emission signal analysis, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 3 (1987) pp. 1868–1875
28.83 X.A. Wu, N. Burkhard, B. Heyneman, R. Valen, M.R. Cutkosky: Contact event detection for robotic oil drilling, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (2014) pp. 2255–2261
28.84 S. Omata: Real time robotic tactile sensor system for the determination of the physical properties of biomaterials, Sens. Actuators A Phys. **112**(2/3), 278–285 (2004)
28.85 S.B. Backus, A.M. Dollar: Robust resonant frequency-based contact detection with applications in robotic reaching and grasping, IEEE/ASME Trans. Mechatron. **19**(5), 1552–1561 (2014)
28.86 M.R. Tremblay, M.R. Cutkosky: Estimating friction using incipient slip sensing during a manipulation task, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 1 (1993) pp. 429–434
28.87 E.G.M. Holweg, H. Hoeve, W. Jongkind, L. Marconi, C. Melchiorri, C. Bonivento: Slip detection by tactile sensors: Algorithms and experimental results, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 4 (1996) pp. 3234–3239
28.88 I. Fujimoto, Y. Yamada, T. Maeno, T. Morizono, Y. Umetani: Identification of incipient slip phenomena based on the circuit output signals of PVDF film strips embedded in artificial finger ridges, Trans. Soc. Instrum. Control Eng. **40**(6), 648–655 (2004)
28.89 B. Choi, H.R. Choi, S. Kang: Development of tactile sensor for detecting contact force and slip, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (2005) pp. 2638–2643
28.90 P.A. Schmidt, E. Maël, R.P. Würtz: A sensor for dynamic tactile information with applications in human–robot interaction and object exploration, Robotics Auton. Syst. **54**(12), 1005–1014 (2006)
28.91 R.D. Howe: Tactile sensing and control of robotic manipulation, Adv. Robotics **8**(3), 245–261 (1993)
28.92 C. Melchiorri: Slip detection and control using tactile and force sensors, IEEE/ASME Trans. Mechatron. **5**(3), 235–243 (2000)
28.93 C.M. Oddo, L. Beccai, G.G. Muscolo, M.C. Carrozza: A biomimetic MEMS-based tactile sensor array with fingerprints integrated in a robotic fingertip for artificial roughness encoding, Proc. IEEE Int. Conf. Robotics Biomim. (2009) pp. 894–900
28.94 A. Schmitz, M. Maggiali, L. Natale, B. Bonino, G. Metta: A tactile sensor for the fingertips of the humanoid robot iCub, Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (2010) pp. 2212–2217
28.95 L.P. Jentoft, Y. Tenzer, D. Vogt, R.J. Wood, R.D. Howe: Flexible, stretchable tactile arrays from MEMS barometers, Proc. 16th Int. Conf. Adv. Robotics (2013) pp. 1–6
28.96 R.S. Fearing, J.M. Hollerbach: Basic solid mechanics for tactile sensing, Int. J. Robotics Res. **4**(3), 40–54 (1985)
28.97 W. Griffin, W.M. Provancher, M.R. Cutkosky: Feedback strategies for telemanipulation with shared control of object handling forces, Presence Teleoperations Virtual Environ. **14**(6), 720–731 (2005)
28.98 H. Maekawa, K. Tanie, K. Komoriya, M. Kaneko, C. Horiguchi, T. Sugawara: Development of a finger-shaped tactile sensor and its evaluation by active touch, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 2 (1992) pp. 1327–1334
28.99 R.S. Fearing: Tactile sensing mechanisms, Int. J. Robotics Res. **9**(3), 3–23 (1987)
28.100 G. Cannata, M. Maggiali, G. Metta, G. Sandini: An embedded artificial skin for humanoid robots, Proc. IEEE Int. Conf. Muiltisens. Fusion Integr. Intell. Syst. (2008) pp. 434–438
28.101 M.-Y. Cheng, X.-H. Huang, C.-W. Ma, Y.-J. Yang: A flexible capacitive tactile sensing array with floating electrodes, J. Micromechanics Microengineering **19**(11), 115001 (2009)
28.102 Y. Hasegawa, M. Shikida, D. Ogura, Y. Suzuki, K. Sato: Fabrication of a wearable fabric tactile sensor produced by artificial hollow fiber, J. Micromechanics Microengineering **18**(8), 085014 (2008)
28.103 D. McConnell Aukes, M.R. Cutkosky, S. Kim, J. Ulmen, P. Garcia, H. Stuart, A. Edsinger: Design and testing of a selectively compliant underactuated hand, Int. J. Robotics Res. **33**(5), 721–735 (2014)
28.104 O. Kerpa, K. Weiss, H. Worn: Development of a flexible tactile sensor system for a humanoid robot, Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS) (2003) pp. 1–6
28.105 D. Bloor, A. Graham, E.J. Williams, P.J. Laughlin, D. Lussey: Metal–polymer composite with nanostructured filler particles and amplified physical properties, Appl. Phys. Lett. **88**(10), 102103 (2006)
28.106 Peratech: Peratech QTC, http://www.peratech.com/standard-products/ (2014)
28.107 T. Someya: Integration of organic field-effect transistors and rubbery pressure sensors for artificial skin applications, Proc. IEEE Int. Electron. Dev. Meet. (2003) pp. 8–14
28.108 H. Alirezaei, A. Nagakubo, Y. Kuniyoshi: A tactile distribution sensor which enables stable measurement under high and dynamic stretch, Proc. IEEE Symp. 3D User Interfaces (2009) pp. 87–93
28.109 Y.-L. Park, B.-R. Chen, R.J. Wood: Design and fabrication of soft artificial skin using embedded microchannels and liquid conductors, IEEE Sens. J. **12**(8), 2711–2718 (2012)
28.110 R. Kageyama, S. Kagami, M. Inaba, H. Inoue: Development of soft and distributed tactile sensors

and the application to a humanoid robot, Proc. IEEE Int. Conf. Syst. Man Cybern., Vol. 2 (1999) pp. 981–986
28.111 B.J. Kane, M.R. Cutkosky, G.T.A. Kovacs: A traction stress sensor array for use in high-resolution robotic tactile imaging, J. Microelectromechanical Syst. **9**(4), 425–434 (2000)
28.112 H. Takao, K. Sawada, M. Ishida: Monolithic silicon smart tactile image sensor with integrated strain sensor array on pneumatically swollen single-diaphragm structure, IEEE Trans. Electron. Dev. **53**(5), 1250–1259 (2006)
28.113 K. Noda, I. Shimoyama: A Shear stress sensing for robot hands -Orthogonal arrayed piezoresistive cantilevers standing in elastic material-, Proc. 14th Symp. Haptic Interfaces Virtual Env. Teleoperator Syst. (2006) pp. 63–66
28.114 M.-Y. Cheng, C.-L. Lin, Y.-J. Yang: Tactile and shear stress sensing array using capacitive mechanisms with floating electrodes, 2010 IEEE 23rd Int. Conf. Micro Electro Mech. Syst. (2010) pp. 228–231
28.115 P. Valdastri, S. Roccella, L. Beccai, E. Cattin, A. Menciassi, M.C. Carrozza, P. Dario: Characterization of a novel hybrid silicon three-axial force sensor, Sens. Actuators A **123/124**, 249–257 (2005)
28.116 S.C.B. Mannsfeld, B.C.-K. Tee, R.M. Stoltenberg, C.V.H.H. Chen, S. Barman, B.V.O. Muir, A.N. Sokolov, C. Reese, Z. Bao: Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers, Nat. Mater. **9**(10), 859–864 (2010)
28.117 R. Brockett: Robotic hands with rheological surfaces, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1985) pp. 942–946
28.118 K.B. Shimoga, A.A. Goldenberg: Soft robotic fingertips. I. A comparison of construction materials, Int. J. Rob, Res. **15**(4), 320–350 (1996)
28.119 A. Mazid, R. Russell: A robotic opto-tactile sensor for assessing object surface texture, IEEE Conf. Robotics Autom. Mechatronics (2006) pp. 1–5
28.120 L.S. Lincoln, S.J.M. Bamberg, E. Parsons, C. Salisbury, J. Wheeler: An elastomeric insole for 3-axis ground reaction force measurement, Proc. IEEE RAS/EMBS Int. Conf. Biomedical Robotics Biomech. (2012) pp. 1512–1517
28.121 H. Shinoda, K. Matsumoto, S. Ando: Acoustic resonant tensor cell for tactile sensing, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 4 (1997) pp. 3087–3092
28.122 H. Shinoda, S. Sasaki, K. Nakamura: Instantaneous evaluation of friction based on ARTC tactile sensor, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 3 (2000) pp. 2173–2178
28.123 S. Ando, H. Shinoda, A. Yonenaga, J. Terao: Ultrasonic six-axis deformation sensing, IEEE Trans. Ultrason. Ferroelectr. Freq. Control. **48**(4), 1031–1045 (2001)
28.124 P. Dario, D. De Rossi, C. Domenici, R. Francesconi: Ferroelectric polymer tactile sensors with anthropomorphic features, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1984) pp. 332–340
28.125 D.M. Siegel: *Contact sensors for dextrous robotic hands*, MIT Artificial Intelligence Laboratory Tech. Rep., no. 900 (MIT Press, Cambridge 1986)
28.126 J.S. Son, E.A. Monteverde, R.D. Howe: A tactile sensor for localizing transient events in manipulation, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 1 (1994) pp. 471–476
28.127 B.S. Eberman, J.K. Salisbury: Determination of Manipulator Contact Information from Joint Torque Measurements. In: *Experimental Robotics I, The First International Symposium*, ed. by V. Hayward, O. Khatib (Springer, Montreal 1990)
28.128 A. Bicchi: Intrinsic contact sensing for soft fingers, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1990) pp. 968–973
28.129 P. Dario: Tactile sensing for robots: Present and future. In: *The Robotics Review 1*, ed. by O. Khatib, J. Craig, T. Lozano-Perez (MIT Press, Cambridge 1989) pp. 133–146
28.130 J.R. Phillips, K.O. Johnson: Tactile spatial resolution III: A continuum mechanics model of skin predicting mechanoreceptor responses to bars, edges and gratings, J. Neurophysiol. **46**(6), 1204–1225 (1981)
28.131 T. Speeter: A tactile sensing system for robotic manipulation, Int. J. Robotics Res. **9**(6), 25–36 (1990)
28.132 K.L. Johnson: *Contact Mechanics* (Cambridge Univ. Press, Cambridge 1985)
28.133 S. Timoshenko, J.N.N. Goodier: *Theory of Elasticity* (McGraw-Hill, New York 1951)
28.134 G. Kenaly, M. Cutkosky: Electrorheological fluid-based fingers with tactile sensing, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1989) pp. 132–136
28.135 R.D. Howe: Dynamic Tactile Sensing, Ph.D. Thesis (Stanford University, Stanford 1990)
28.136 R.M. Voyles, B.L. Stavnheim, B. Yap: Practical electrorheological fluid-based fingers for robotic applications, IASTED Int. Symp. Robotics Manuf. (1989)
28.137 J.J. Clark: A magnetic field based compliance matching sensor for high resolution, high compliance tactile sensing, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1989) pp. 772–777
28.138 T.H. Speeter: Analysis and Control of Robotic Manipulation, Ph.D. Thesis (Case Western Reserve University, Cleveland 1987)
28.139 R. Fearing: Tactile sensing for shape interpretation. In: *Dextrous Robot Hands*, ed. by S.T. Venkataraman, T. Iberall (Springer, Berlin, Heidelberg 1990) pp. 209–238
28.140 A.J. Worth, R.R. Spencer: A neural network for tactile sensing: The hertzian contact problem, Proc. Int. Jt. Conf. Neural Netw. (1989) pp. 267–274
28.141 W.E.L. Grimson, T. Lozano-Perez: Model-based recognition and localization from sparse range or tactile data, Int. J. Robotics Res. **3**(3), 3–35 (1984)
28.142 P.C. Gaston, T. Lozano-Perez: Tactile recognition and localization using object models: The case of polyhedra on a plane, Proc. IEEE Trans. Pattern Anal. Mach. Intell. (1984) pp. 257–266

28.143 J.L. Schneiter: An objective sensing strategy for object recognition and localization, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1986) pp. 1262–1267
28.144 R. Cole, C. Yap: Shape from probing, J. Algorithm. **8**(1), 19–38 (1987)
28.145 P.K. Allen: Mapping haptic exploratory procedures to multiple shape representations, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1990) pp. 1679–1684
28.146 R.E. Ellis: Extraction of tactile features by passive and active sensing, Proc. SPIE 0521 (1985) p. 289
28.147 S.J. Lederman, R. Browse: The physiology and psychophysics of touch. In: *Sensors and Sensory Systems for Advanced Robotics*, ed. by P. Dario (Springer, Berlin, Heidelberg 1986) pp. 71–91
28.148 H. Ozaki, S. Waku, A. Mohri, M. Takata: Pattern recognition of a grasped object by unit-vector distribution, IEEE Trans. Syst. Man Cybern. **12**(3), 315–324 (1982)
28.149 R.L. Klatzky, R. Bajcsy, S.J. Lederman: Object exploration in one and two fingered robots, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1987) pp. 1806–1809
28.150 D. Siegel: Finding the pose of an object in the hand, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1991) pp. 406–411
28.151 D. Taddeucci, C. Laschi, R. Lazzarini, R. Magni, P. Dario, A. Starita: An approach to integrated tactile perception, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 4 (1997) pp. 3100–3105
28.152 A. Schneider, J. Sturm, C. Stachniss, M. Reisert, H. Burkhardt, W. Burgard: Object identification with tactile sensors using bag-of-features, IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS) (2009) pp. 243–248
28.153 N. Gorges, S.E. Navarro, D. Göger, H. Wörn: Haptic object recognition using passive joints and haptic key features, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (2010) pp. 2349–2355
28.154 Y. Bekiroglu, J. Laaksonen, J.A. Jorgensen, V. Kyrki, D. Kragic: Assessing grasp stability based on learning and haptic data, IEEE Trans. Robotics **27**(3), 616–629 (2011)
28.155 V.S. Gurfinkel: Tactile sensitizing of manipulators, Eng. Cybern. **12**(6), 47–56 (1974)
28.156 R. Ellis: Acquiring tactile data for the recognition of planar objects, Proc. IEEE Int. Conf. Robotics Autom. (ICRA), Vol. 4 (1987) pp. 1799–1805
28.157 A. Cameron: Optimal tactile sensor placement, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1989) pp. 308–313
28.158 P. Dario: Sensing body structures by an advanced robot system, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1988) pp. 1758–1763
28.159 S.A.A. Stansfield: Robotic grasping of unknown objects: A knowledge-based approach, Int. J. Robotics Res. **10**(4), 314–326 (1991)
28.160 A. Petrovskaya, O. Khatib: Global localization of objects via touch, IEEE Trans. Robotics **27**(3), 569–585 (2011)
28.161 N.F. Lepora, U. Martinez-Hernandez, H. Barron-Gonzalez, M. Evans, G. Metta, T.J. Prescott: Embodied hyperacuity from Bayesian perception: Shape and position discrimination with an iCub fingertip sensor, IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS) (2012) pp. 4638–4643
28.162 C. Muthukrishnan, D. Smith, D. Meyers, J. Rebman, A. Koivo: Edge detection in tactile images, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (1987) pp. 1500–1505
28.163 A.D. Berger, P.K. Khosla: Using tactile data for real-time feedback, Int. J. Robotics Res. **10**(2), 88–102 (1991)
28.164 K. Pribadi, J.S. Bay, H. Hemami: Exploration and dynamic shape estimation by a robotic probe, IEEE Trans. Syst. Man Cybern. **19**(4), 840–846 (1989)
28.165 H. Zhang, N.N. Chen: Control of contact via tactile sensing, IEEE Trans. Robotics Autom. **16**(5), 482–495 (2000)
28.166 A.M. Okamura, M.R. Cutkosky: Feature detection for haptic exploration with robotic fingers, Int. J. Robotics Res. **20**(12), 925–938 (2001)
28.167 K. Suwanratchatamanee, M. Matsumoto, S. Hashimoto: Robotic tactile sensor system and applications, IEEE Trans. Ind. Electron. **57**(3), 1074–1087 (2010)
28.168 K. Yamada, K. Goto, Y. Nakajima, N. Koshida, H. Shinoda: A sensor skin using wire-free tactile sensing elements based on optical connection, Proc. 41st SICE Annu. Conf., Vol. 1 (2002) pp. 131–134
28.169 M. Schoepfer, C. Schuermann, M. Pardowitz, H. Ritter: Using a piezo-resistive tactile sensor for detection of incipient slippage, Proc. ISR/ROBOTIK 41st Int. Symp. Robotics (2010) pp. 14–20
28.170 B. Heyneman, M.R. Cutkosky: Slip interface classification through tactile signal coherence, IEEE/RSJ IEEE Int. Conf. Intell. Robots Syst. (IROS) (2013) pp. 801–808
28.171 P. Dario, P. Ferrante, G. Giacalone, L. Livaldi, B. Allotta, G. Buttazzo, A.M. Sabatini: Planning and executing tactile exploratory procedures, IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS), Vol. 3 (1992) pp. 1896–1903
28.172 S.C. Jacobsen, J.E. Wood, D.F. Knutti, K.B. Biggers: The Utah/MIT dextrous hand: Work in progress. In: *First International Conference on Robotics Research*, ed. by M. Brady, R.P. Paul (MIT Press, Cambridge 1984) pp. 601–653
28.173 H. Shinoda, H. Oasa: Passive wireless sensing element for sensitive skin, IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS), Vol. 2 (2000) pp. 1516–1521
28.174 M. Hakozaki, H. Shinoda: Digital tactile sensing elements communicating through conductive skin layers, Proc. IEEE Int. Conf. Robotics Autom. (ICRA'02), Vol. 4 (2002) pp. 3813–3817
28.175 L. Ascari, P. Corradi, L. Beccai, C. Laschi: A miniaturized and flexible optoelectronic sensing system for a tactile skin, Int. J. Micromechanics Microengineering **17**, 2288–2298 (2007)
28.176 M. Zillich, W. Feiten: A versatile tactile sensor system for covering large and curved surface areas, IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS) (2012) pp. 20–24