A Survey of Robot Tactile Sensing Technology

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Abstract

This paper reviews the current state-of-the-art in tactile sensing technology. We examine in detail the different methods of transduction employed by tactile sensors and describe various significant designs that incorporate these methods. We then describe the different techniques used to process and analyze tactile data. Finally, we conclude with an assessment of the current state of development.

1. Introduction

Tactile sensors are an important class of sensors for robotics. This paper defines a tactile sensor to be a device which measures parameters of a contact interaction between the device and some physical stimuli. The interaction is normally confined to a touch sensitive region of the device's surface.

Tactile sensors are used to sense a diversity of properties, concerning both attributes of the stimulus itself and the relationship between the stimulus and sensor. A binary contact sensor for detecting presence or absence of touch is a tactile sensor. A more complex tactile sensor consists of a continuously sampled two-dimensional array of sensing sites. Such a sensor may provide data on the size, shape, position, thermal conductivity, and distribution of forces of a contacting stimulus. Tactile sensors have been developed to sense slip, torque, normal forces, three-dimensional shape, and thermal properties.

The dimensionality of a sensor refers to the spatial arrangement of the individual sensing sites and falls into three basic classes:

1. Zero dimension: there is a single tactile sensitive site, for example, a limit switch or a gripper-jaw contact sensor.
2. One dimension: there are several sensing sites, all arranged collinearly.
3. Two dimensions: there are sensing sites distributed over the area of the sensing surface, usually in a regular pattern.

The main categories of data which tactile sensors transduce are

1. Simple contact: the presence or absence of contact between sensor and stimulus.
2. Magnitude of force: a numerical value transduced from each site represents the amount of force applied by the stimulus at that site; note that the force sensed may be torque, shear, force normal to sensor surface, etc.
3. Three-dimensional shape: the transduction process gives numerical values directly related to the three-dimensional shape of an object touching the sensor; for example, linear displacement of an array of probes.
4. Slip: the data indicates the movement of a contacting stimulus relative to the sensor surface. Typically, a slip sensor is mounted on a robot gripper.
5. Thermal properties: the thermal conductivity of a contacting stimulus, as well as its absolute temperature, can be measured through contact.

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These are the main properties which are transduced by tactile sensors and give rise to the raw data values output by the sensor prior to any kind of processing and analysis. One sensor may be capable of transducing more than one property. There are other properties which tactile sensors have the potential to transduce, such as texture, hardness, dryness, etc., but, as is shown in this paper, very few practical examples of these are documented.

Tactile sensors provide data that is input to a computing system. The acquisition, processing, and manipulation of this data constitutes tactile sensing. Having defined the term *tactile sensing* as it pertains to this review, we consider definitions quoted by other authors and organizations. The Robotics Institute of America defines tactile sensing to be "the continuous monitoring of forces in an array" (Gindy 1983), while the late Professor Leon Harmon considered it to be "the graded sensing of contact forces in an array of points" (Harmon 1984). In addition, the Robotics Institute regards *touch* sensing as being the sensing of force at one or just a few points. The above quotations place emphasis on the sensing of the magnitude and location of forces. While many tactile sensors can sense force magnitudes and locations, a number of examples have been built which do not quite match the definitions quoted above. A wider definition is therefore used throughout this paper.

Tactile sensing has received an increasing amount of attention since the early 1980s, with a number of new sensors and tactile data processing approaches publicized. It is still a sensing modality that is very much in its infancy when compared, for example, with developments in machine vision. One reason for the lack of sophisticated tactile sensing in industrial robot applications is due to the scarcity of robust, reliable, accurate, and high-resolution sensors. The technology of tactile sensors is now evolving into more suitable designs, and it is expected that they will take a more prominent role in robotics in the near future.

The next section examines in detail the different methods of transduction employed by tactile sensors and describes various significant designs that incorporate these methods. This is followed by a look at the different techniques used to process and analyze tactile data, concluding with an assessment of the current state of development.

2. Tactile Sensor Designs

2.1. Introduction

Much tactile domain research has been directed toward developing new tactile sensor designs to provide reliable and accurate tactile data. Most of the designs are tactile sensor arrays, consisting of a grid or matrix of sensing sites, each site known as a *tactel* (derived from *tactile element*). The term *taxel* is sometimes used, but this can be confused with the texture analysis term *texel.* Tactile sensor designs vary notably in terms of the spatial resolution and sensitivity of elements, and use a variety of transduction methods.

Harmon, at Case Western Reserve University, carried out a survey and analysis of the need for tactile sensing (Harmon 1982). He sent a questionnaire to 55 persons in academic, industrial, government, and private sectors, asking about their views on tactile sensor specifications, systems, applications, problems, and economics. As a result, he was able to devise a list of specifications for a practical tactile sensor, as well as identify the major application areas and problems within tactile sensing. His survey is a useful guide to tactile sensing, although it is becoming dated now as the detailed literature search which he carried out only covers up to November 1980. Nevertheless, the specification list is a useful guide for the designer.

The resulting set of tactile sensor requirements is summarized as follows:

1. The sensor surface should be both compliant and durable.
2. Spatial resolution should be 1–2 mm.
3. A range of 50–200 tactels is acceptable (e.g., 5×10, 10×20).
4. The sensor should be able to detect as little as 5 g (0.049 N), ideally 1 g (0.0098 N).
5. A dynamic range of 1000:1 is satisfactory.
6. The sensor must be stable, repeatable, and without hysteresis.
7. The response must be monotonic, though not necessarily linear.
8. The time resolution for the sensor should be at least 100 Hz.

Fig. 1. Resistive tactile element: resistance measured through the thickness of the rubber.

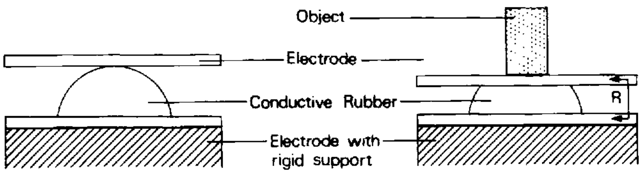
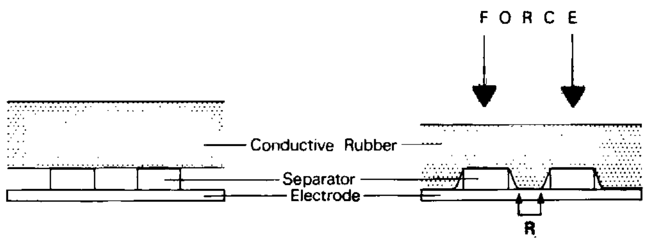


Fig. 2. Resistive tactile element: resistance measured across the rubber.



In addition, it is desirable that a tactile sensor carry out local data processing to provide compact and high-level information for any robot system to which it may be connected.

The above list is a mixture of absolute requirements and suggested likely specifications. Points 1, 6, and 7 must be present in any practical sensor, while the others are suggestions, particularly with respect to the number of elements and spatial resolution. They should certainly not be regarded as maxima, and the precise requirements are clearly affected by the intended application domain.

Having outlined the desirable characteristics of tactile sensors, we next examine in detail the different transduction methods employed and describe some of the significant sensors which have been publicized. Some other reviews of tactile hardware can be found in Harmon (1984), Dario and De Rossi (1985), and Pennywitt (1986). A discussion of tactile sensing design issues is presented in Jacobsen et al. (1987). Another interesting review is Lauber et al. (1988), which concludes that tactile sensing should be combined with other senses for optimal adaptive robotics.

2.2. Methods of Transduction

Several techniques have been used to transduce the interaction between a contacting stimulus and a tactile sensor into data suitable for computer analysis. The main classes and variants are described below.

2.2.1. Resistive and Conductive

The transduction method which has received most attention in tactile sensor design is concerned with the change in resistance of a conductive material under applied pressure. This technique involves measuring the resistance either through or across the thickness of a conductive elastomer. The measured resistance changes with the amount of force applied to the material, resulting from the deformation of the elastomer altering the particle density within it. Most commonly used elastomers are made from carbon or silicon doped rubber, and the construction is such that the sensor is made up of a grid of discrete sites at which the resistance is measured. Figures 1 and 2 illustrate this.

Early designs demonstrating that the principle could be incorporated into tactile arrays are described in Snyder and St. Clair (1978) and Briot (1979).

Larcombe, at the University of Warwick, UK, investigated the use of carbon fibers for tactile sensors (Larcombe 1981). Carbon fibers are filaments of carbon created by baking certain forms of unspun textile yarns and are cylindrical in cross section. When two fibers rest in contact with one another, the area of contact is very small, but when they are pushed together, the contact area increases, thereby increasing the electrical conductivity at the junction. The fibers are grouped into bundles, and these bundles can be arranged into an orthogonal grid to form a tactile sensor array. Typically, the unloaded resistance at bundle junctions is 2 kΩ, reducing to around 200 Ω for a 5-kg (49.05-N) load.

An implementation of a tactile sensor array using carbon is described by Robertson and Walkden (1986). They built a 256-element array around a mat of carbon fibers. On top of the mat are placed rows of electrodes parallel to each other, and underneath are further parallel electrodes arranged perpendicular to the top row. The bottom electrodes are etched on a printed circuit board (PCB). The sensor is scanned by applying reference voltages to top and bottom electrode rows, and then measuring resistance at the junction between these two rows. The output is exponential with a small amount of hysteresis over a practical load range of 0 to 600 kPa. Transducer life is about 2 million cycles. This device is also interesting because it is integrated into a sensing system that provides local image analysis, corrections for tactel nonuniformities, and detection of overload.

Another sensor using a carbon felt was built in France (Pruski and Mutel 1984). A simple tactile array was built based on measuring the voltage through the felt, as described earlier. However, a significant aspect of their design is that the same principle is used to create a slip sensor. Noise generated by the tufted carbon felt as an object slips across it is measured and processed by simple logic into a binary output signal. A single layer of felt has two electrodes attached to its lower face. As an object moves on the sensor surface, the long tufted carbon fibers are displaced and generate noise. Appropriate circuitry detects the noise and outputs a signal above a predefined threshold. A working sensor has been constructed and tested.

One other carbon-based sensor was developed at Carnegie-Mellon University (Christ and Sanderson 1982). A grid of conductors was formed on carbon-impregnated foam, perpendicular conductors being on opposite faces of the foam. When compressed, the resistance decreases, and thus a tactile sensor can be constructed. A 16×16 array with $\frac{1}{4}$-inch resolution and 256:1 pressure scale was built and incorporated into a tactile recognition system. Problems with elasticity of the conductors and the foam were experienced, and the sensor was noisy in the unloaded state. This was due to vibrations displacing the conductors which only lightly rest on the foam. However, it performed well in a simple recognition task.

A design using carbon-loaded rubber originated by Purbrick at MIT formed the basis for several later designs (Purbrick 1981). It was constructed from a simple grid of silicon rubber conductors, each conductor, or "cord," being D-shaped in cross section. Resistance at cord junctions was measured and provided reliable output between 50-g (0.491-N) and 500-g (4.91-N) loads. However, some creep, the phenomenon of gradual increasing sensor output for constant load, was exhibited, and pressure variations were difficult to discriminate.

Following on from Purbrick was a design by Hillis (1982). This device has a flexible printed circuit board etched in one direction with a sheet of anisotropically conductive rubber (ACS) placed above it. The ACS material is conductive along one axis, which is placed orthogonal to the PCB etchings to form the familiar grid pattern. A separator is used to keep the ACS away from the PCB in the unloaded state.

An important point to note about this design is that the elastomer is squeezed onto the electrode; hence the contact resistance, not the internal resistance through the elastomer, is measured. The separator, therefore, not the elastomer, determines the sensitivity and dynamic range of the sensor. A 16×16 tactel array with 1–100 g (0.0098–0.98 N) range was built and inserted on a tendon actuated finger. It was successfully used in object recognition tasks.

One of the few commercial tactile sensors currently available was influenced by the work of Purbrick and Hills. The Barry Wright Corporation Sensoflex tactile sensor is based around a matrix of elastomeric conductive rods, the two layers being separated by nonconductive elastomers. A 16×16 array with 0.1-inch center-to-center spacing over an active area of 1.56 inches $\times$ 1.56 inches is available, or alternatively, an 8×16 array with 0.05-inch spacing over 0.38 inch $\times$ 0.78 inch (Peterson 1984). The sensor is repeatable, has low hysteresis, and has minimal set (nonrecovered deformation after removal of load).

A sensor developed at University of Massachusetts, Amherst, uses a carbon-doped cord at each sensing site (Overton 1984). This cord is bent into a hoop so that both ends touch a PCB. The hoops are embedded within silicon rubber. It is this which comes into contact with any objects, thereby protecting the transducing medium. A sensor of 128 sites/in^2 was constructed of 16×8 tactels, with a correction process used to derive a 16×16 image from the raw data. The sensor has a dynamic range of about 150:1 and is able to withstand significant overload. Noise in the unloaded state is about 1–2% of the full scale, and there is some hysteresis, due to the scanning electronics and also the interaction between the silicon rubber pad and the contact array.

Marc Raibert has produced tactile sensor designs incorporating novel features. The first design is both a tactile processing computer and a tactile array sensor (Raibert and Tanner 1982.). A conductive sheet rubber is placed over a PCB, and the resistivity of the sheet is measured. The significant feature of this design is that the PCB incorporates VLSI circuitry so that each tactel not only transduces its data but processes it as well. Each site performs transduction and processing operations at the same time as all the others. The computer is thus a parallel processor.

As a prototype, a 6×3 element sensor was built with 1-mm^2 spatial resolution and 1 bit/tactel data. The main problems were that the Dynacon rubber used exhibited some hysteresis, was nonrugged, and produced a blob-shaped receptive field. It is also difficult to construct small analog circuits on a digital chip as required by this design. However, the VLSI approach was demonstrated to be viable, and alleviated the problems of wiring up each site and having to process the data serially.

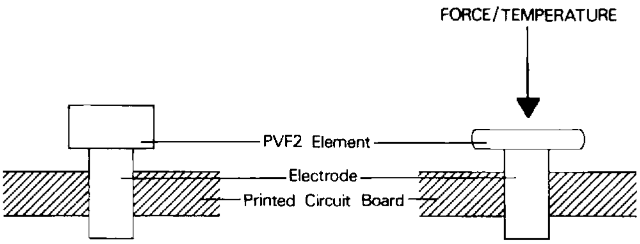
In another design (Raibert 1984), Hillis's approach is taken a stage further. In the Hillis sensor (Hillis 1982), the separator between the layers of conductors determines the sensitivity and spatial resolution of the device. Raibert adopts a similar approach, which allows the elastic material to be optimized for mechanical properties independently of its electrical properties. This is because it is the contact resistance, not internal resistance of the elastomer, which is significant here. A PCB at the base of the sensor has an array of notchlike holes, with electrodes at the bottom of the holes. The elastomer rests on the top, and applied pressure forces the rubber into the holes and into contact with the electrodes. Differently shaped, but basically triangular, holes produce different responses: typically logarithmic, linear, or exponential. VLSI circuitry is used to multiplex sensing elements; consequently, only five wires into the sensor are needed. An experimental design of 48 elements, each one 0.3 mm $\times$ 0.6 mm, providing 4 bits of data has been built and is under evaluation. It is promising, since response characteristics may be altered by changing the hole configuration. Also, VLSI techniques enable the processing of data before it leaves the sensor, as demonstrated by the first design.

A tactile sensor that has been used extensively in various experiments at the University of Pennsylvania is built in the form of a probe (Bajcsy and Goldberg 1984). The sensor was donated by G. Giralt of LAAS, Toulouse. The finger has 133 electrodes covered by a variable-resistance rubber layer. As pressure is applied, the voltage drop at each electrode is measured and turned into a binary value. The sensor acts as a probe rather than as a planar device, since it has 12 faces, connected to 12 facets that meet at the sensor tip. Each face has 10 electrodes arranged in a straight line, each facet has a single electrode, and there is an electrode on the tip as well, to give 133 tactels. The probe was mounted on an *X-Y-Z* positioning device (Wolfeld 1981) and used in profile tracing experiments, described below.

Some other sensors constructed using silicon rubber are to be found in Chalupa, Marik, and Volf (1982), van Brussel and Belien (1986), and Grant, Mowforth, and Jackson (1986). The first of these has 16×32 and 7×21 tactels on the palm of a hand, with 3.2-mm center-to-center spacing. Shape classification experiments of grasped objects proved to be 98% successful, discriminating squares, rectangles, circles, ellipses, etc. The sensor built by van Brussel has 16×16 elements with 1.2-mm resolution, a pressure range of 10 to 500 kPa represented over 16 levels of output. Minor creep and hysteresis are present, but the rubber is very durable, about 10 million cycles. The simple 2×2 sensor made by Grant et al. is constructed using silicon rubber made by Flexigage Ltd. of Glasgow, UK. This material is also used in strain gauge applications. Silicon rubber is also used in the designs of Russell (1987), Kah-Bin and Yoon-Song (1988), and Ghani (1988). The latter sensor is a 32×32 tactel pad incorporating scanning electronics that serially transmit tactile images to a purpose-built tactile processing module. Its commercial exploitation is being undertaken by MARI Advanced Electronics Ltd., of Newcastle-upon-Tyne, UK.

The conductive and resistive approach to tactile transduction has probably received the most attention, and a number of designs have been quite successful. A wide dynamic range can be attained with considerable durability. Hysteresis and creep are present in most designs, probably because of the reliance on elastomers. The problem of wiring is partially solved by using scanning techniques, reducing the number of wires required by an $N \times M$ sensor to $N + M$. This technique is also compatible with printed circuit technology, as demonstrated notably by Raibert and Tanner.

Fig. 3. Piezoelectric/pyroelectric tactile element.



2.2.2. Piezoelectric and Pyroelectric Effects

Sensors based around the piezoelectric effect are rather different from the resistive devices described above. The piezoelectric effect is the generation of a voltage across the sensing element when pressure is applied to it (Fig. 3). The voltage generated is proportionally related to the applied pressure. No external voltage is required, and a continuous analog output is available from such a sensor. Correspondingly, the pyroelectric effect is the generation of a voltage when the sensing element is heated or cooled. An important feature of such sensors is that they are inherently dynamic. If a load is applied and maintained, or the temperature is constant, then the sensor output decays to zero. Such sensors are most suited for sensing pressure changes or thermal variations.

Polymeric materials with piezoelectric and pyroelectric properties are appropriate for use with tactile sensors. Quartz and some ceramics have piezoelectric properties but are fragile; however, a polymer known as polyvinylidene fluoride (PVF_2 or PVDF) has been used successfully. PVF_2 has good mechanical properties and is a durable material, thereby making a good tactile sensing surface. It is not normally piezoelectric in its raw state, but can easily be made so by suitably orienting the PVF_2 sample and applying a high electric field (Dario et al. 1984). It then becomes highly piezo- and pyroelectric with a wide dynamic range. It can be made as thin as 5 microns and up to 2 mm thick, and may be molded into various forms; hence PVF_2 has a number of attractions when considering tactile sensor materials.

A problem with piezoelectric sensors is scanning an array of sensing elements. The row-column scanning system for accessing data from each tactel, which minimizes the number of wires required, is difficult to implement on a piezoelectric sensor. The generated charge needs to be collected individually, requiring discrete charge amplifiers, one per tactel, and screening is necessary to reduce electrical interference. Another problem with PVF_2 is separating the piezoelectric effects from the pyroelectric effects since both may be present; thus protection from thermal variations may be necessary if pressure variations are important.

One of the primary exponents of piezo- and pyroelectric tactile sensors is the workers at the Centro "E. Piaggio," University of Pisa. They developed a PVF_2-based sensor to detect both pressure and thermal changes, with multiple sensory layers analogous to the dermal and epidermal layers in human skin.

The sensor consists of eight layers, the outermost layer being a protective film (Dario et al. 1984; Dario and De Rossi 1985). The base of the sensor is a PCB on which metal electrodes are fixed. A layer of PVF_2 is bonded to the PCB and is metal-plated on its upper surface. This forms the deep *dermal* sensor. Deformation of this layer causes the piezoelectric effect to generate a voltage which is sensed via the electrodes. On top of the dermal sensor is an elastomer layer above which lie a resistive coating and another PVF_2 layer, the *epidermal* sensor. The epidermal PVF_2 layer has electrodes above and below it connected to conductors.

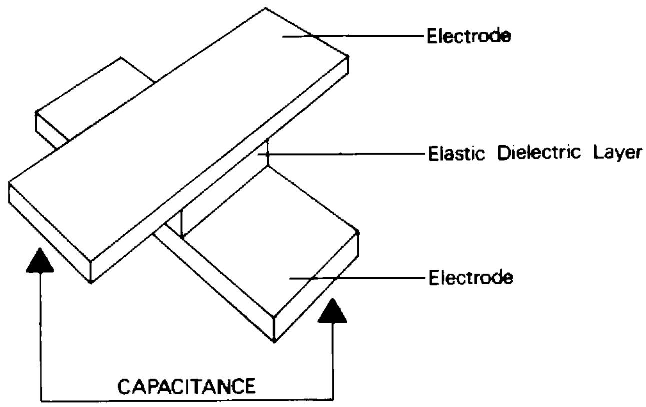
The epidermal layer is protected from a contacting stimulus by a thin Mylar film. The layer is highly sensitive but also susceptible to thermal fluctuations as well as pressure variations. Simple contact data is provided by the epidermal layer, and, when rubbed against an object, the output signal variations give a measure of the roughness of the object's surface.

The resistive coating on the underside of the epidermal sensor is used to form a thermal sensor. The sensor is connected to a power supply causing the device to heat up. When an object touches the sensor surface, heat flows from the paint layer through the epidermal PVF_2 and into the object. The heat flow is related to the thermal conductivity of the object.

Although the pyroelectric component of the epidermal sensor output is a problem, the elastomer layer helps to alleviate the problem for the dermal sensor. The elastomer has low thermal conductivity and so there is a delay of around 1 s before temperature variations affect the dermal sensor output.

The researchers at Pisa also addressed the problem

Fig. 4. Capacitive tactile element.



of scanning an array of piezoelectric sites. A solution is to have one charge output per tactel, but this requires a cumbersome electronics module and is expensive. As an alternative, a design using multiplexing circuits which connect each tactel output to a single charge amplifier was developed. A 64-element matrix was scanned by four 16-channel analog multiplexers which were switched by another multiplexer. The output from each tactel was fed into a single, high-quality, FET-input operational amplifier. Analog-to-digital conversion and interfacing to a tactile image processing system are issues currently under development.

The multilayer sensor of 8 × 16 elements behaved encouragingly in laboratory tests. A dynamic range of 4000 : 1, between 0.01- to 40-N loads was established. Slips of a few hundred microns lasting a few milliseconds were detected. The output from both layers is linear with negligible hysteresis.

A variation on this multilayered sensor is incorporated into an anthropomorphic robotic testbed. The sensor is mounted on a tendon-actuated finger and is intended for exploratory tactile sensing of complex surfaces. One possible use for this setup is in a robot workstation for assisting a disabled person (Dario et al. 1987). Two additional sensing elements are part of the multilayer "fingertip." The first is a "nail," consisting of an elastic structure incorporating a PVF_2 layer acting as a strain gauge. This is intended for sensing textured surfaces by rubbing the nail along the pitted surface and detecting the resultant forces. The second additional sensor is an array of curved ultrasonic transducers made out of PVF_2 film, enabling proximity as well as tactile sensing.

Some other researchers interested in piezoelectric tactile sensors are at the University of Pennsylvania. In Abramowitz et al. (1984), a PVF_2-based sensor for mounting on the Pennsylvania articulated mechanical hand is described. It is proposed that the three-fingered hand will have six 2 × 4 element tactile arrays, one per fingertip and one per second link of the finger. The center-to-center spacing is 4.8 mm, with 3.2-mm-diameter electrodes. Each sensing site is individually wired, with nine wires per sensor pad being carried away from the fingers. The first prototype described suffers from pronounced pyroelectric as well as piezoelectric responses, the individual site wiring problem, and decay of output signal for constant applied loads. In addition, if compliance is introduced to the sensor, mechanical crosstalk becomes significant (greater than 10%). The Pennsylvania researchers also report that piezoelectric effects can be experienced both through the thickness and through the plane of the PVF_2. If the sensor is made compliant, responses from both planes are experienced, causing difficulties in the interpretation of the sensor output. This design illustrates some of the problems associated with simple piezoelectric sensors. Further designs are being worked on to solve these, but, as demonstrated by the Pisa sensor, the solution will be complex.

2.2.3. Capacitive Techniques

Tactile sensors within this category are concerned with measuring capacitance, which is made to vary under applied load. The capacitance of a parallel plate capacitor depends upon the separation of the plates and their area, so that a sensor using an elastomeric separator between the plates provides compliance such that the capacitance will vary according to applied load (Fig. 4). Harmon dismisses such sensors as being too susceptible to external fields and dependent upon specific materials (Harmon 1982), although some researchers have produced practical designs.

At Bell Labs, R. Boie built an 8 × 8 tactile sensor array using capacitive principles (Boie 1984). The sensor consists of an elastic outer layer that is the contacting surface. This is on top of an elastic dielectric layer, which has orthogonal conductive strips above and below it. The lower strips are etched on a PCB.

The familiar matrix pattern of sensing sites is thus established, each site acting as a capacitor. Force readings are obtained by measuring capacitance through the elastic dielectric layer. The capacitive impedance is linearly proportional to the mechanical displacement of the elastic layer. Each element occupies 2.5 mm^2 and can measure pressures up to 5 kPa. It is possible to construct a 32×32 array with current technology, the sensor producing a composite video output. Boie contends that much of the interface attributed to capacitance sensors is actually man-made and can be screened out, although there is some low intrinsic noise. The materials used have both suitable mechanical properties and dielectric properties, and give a wide dynamic range. The widths and separation of the conductive strips determine the spatial resolution, limited by the degree of spread around applied force points.

An extension of the Boie design is described in Siegel, Drucker, and Garabieta (1987). Their 8×8 element sensor is constructed with an electronically insulating dielectric of silicon rubber. A detailed analysis is presented in the paper; a linear response is achieved, and there is no notable hysteresis. This sensor is good for detecting changes but not for absolute values, due to repeatability problems. Siegel, Garabieta, and Hollerbach (1986) discuss a combined force and thermal sensor. The force sensing is achieved using capacitive techniques, while the thermal sensor relies on the principle that heat will flow from a warmer material into a cooler material until their temperatures equalize. The sensor applies heat to a contacting material and measures the rate of temperature change of the surface. The cooling rate is proportional to the contacting material's thermal conductivity.

A design for a 9×9 capacitive tactile sensor is described in Wolffenbuttel and Regtien (1986). This sensor consists of a thin conductive rubber layer placed on top of an isolating intermediate layer, which in turn is attached to a silicon wafer bonded to a ceramic plate. Each element is composed of a 7.5 mm $\times$ 2.0 mm aluminum rectangle on the integrated circuit. A sinusoidal drive voltage is coupled to each selected sensing rectangle through the isolating rubber layer to the upper conductive layer. The thickness of the intermediate layer determines the capacitance, and since applied force will deform the layer, capacitance can be related to pressure. An interesting feature of this design is that edge detection using the Laplace operator is readily achievable in hardware. By applying an appropriate voltage to the neighbors of a selected element, the output of the associated a.c. operated charge amplifier is proportional to the convolution of that element with the Laplace operator. A degree of local processing by the sensor is therefore possible.

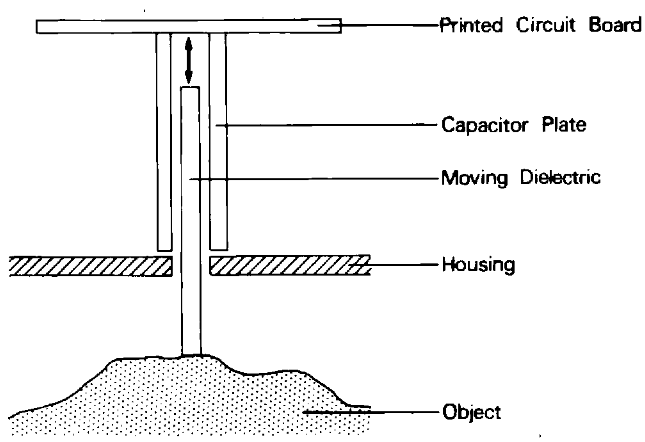


Fig. 5. Mechanical/capacitive tactile element.

A tactile sensor array based on a moving dielectric element has been constructed at the University of Sussex, UK (Jayawant, Onori, and McK.Watson 1986). Each sensing element has two coaxial capacitor cylinders, acting as plates, fixed to a PCB. A dielectric element is in the space between the cylinders. The dielectric is spring mounted and displaced by contact with an external stimulus; hence it moves up and down between the capacitor plates as contact loads vary. A force-displacement relationship is thereby established. A simple 4×4 matrix was built, using 2D scanning techniques to reduce the number of wiring connections necessary. This sensor is physically large, although future models with higher resolution, around 20×15 elements spaced 2 mm apart, are proposed. However, the sensor will still be bulky. One drawback is that the sensor surface is composed of cylindrical pins which are connected to the moving dielectric. The sensor surface is not smooth, and small objects could fall between the pins and be undetected. Figure 5 illustrates a mechanical/capacitive tactile element.

Fearing, at the Standard AI Lab, has developed a 64-element capacitive sensor in the form of a cylinder (Fearing 1987). The sensor is for mounting on the

Fig. 6. Magnetic tactile element.

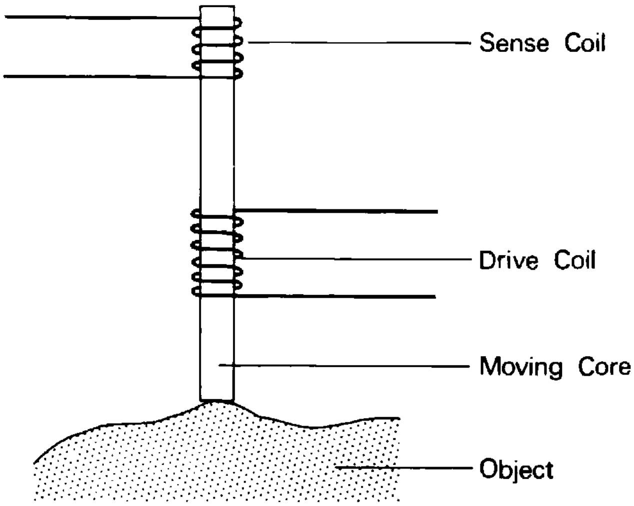
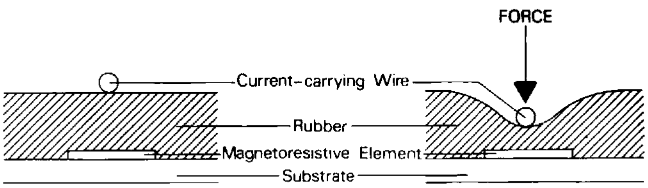


Fig. 7. Magnetoresistive tactile element.



Stanford/JPL tendon-actuated hand (Salisbury and Craig 1982). The cylinder has 7 × 8 tactels, and eight elements are placed on the hemispherical fingertip. The lower plates of the capacitors are eight stripes of copper at 45° intervals around the cylinder axis. The upper plates are seven rings of copper spaced along the length of the cylinder. This sensor was used in various experiments, including "twirling" a small bar held in the three fingers of the hand.

A novel slip sensor using the change in capacitance caused by relative contact movement between sensor and object is described in Luo (1984). The contacting sensor surface comprises a set of parallel rollers. Each roller is a half cylinder of conductive material, and a half cylinder of nonconductive material. The rollers are mounted in a nonconductive material. The casing and rollers act as a variable capacitor. A slipping object will rotate the rollers, causing the capacitance to change, which is then measured, thereby facilitating a slip sensor. The sensor measures the change of phase angle, with the amount of phase shift providing a measure of the scale of slip. A highly linear relationship between detected phase shift angle and sensor output was established.

Capacitance sensors have received little attention, but show some promise. The noise problem seems to be partly soluble, and the sensors give wide dynamic range and are robust. However, capacitance decreases with decreasing physical tactel size, and so stray signals will influence the sensor output for very small sites. Also, some dielectric materials are temperature sensitive, although the papers described above do not mention this problem.

2.2.4. Magnetic Transduction Methods

Sensors using magnetic transduction are divided into two basic categories. The first category groups together sensors which use mechanical movement to produce a change in magnetic flux (Fig. 6). The second category concerns magnetoelastic materials which show a change in magnetic field when subjected to mechanical stress (Fig. 7).

One of the earliest robot tactile sensors is based on the first category of magnetic sensors. First published in 1977, it is reprinted in Sato, Heginbotham, and Pugh (1986). It consists of an 8 × 8 matrix of probes, each probe being energized by a drive coil. The probes are displaced perpendicularly when in contact with a stimulus, to form the contours of the stimulus. The displacement of a probe causes an induced voltage which is measured by a sense coil. The sensor output is then calibrated in terms of probe deflection in millimeters. The sensor is rather cumbersome and suffers from probes jamming when on steep slopes due to side loads and friction. It was used successfully to differentiate objects based upon their contours and was one of few tactile sensor arrays in use in the 1970s.

A one-dimensional sensor using Hall effect integrated circuits is described in Kinoshita, Hajika, and Hattori (1983). The sensor comprises a line of 20 Hall effect integrated circuits, each opposite a magnet. Contact with a stimulus displaces the integrated circuits, producing a change in magnetic flux indicated by the output of the sensing element. This data is calibrated and used to form a profile of the stimulus. The surface of each sensing head is 19 × 14 mm, and the whole sensor is 115 mm long. The practical range of displacement is 0–2.5 mm since above this, the output becomes saturated although movement up to 5 mm is possible. Despite being bulky, the sensor has been mounted on a robot gripper and used in an active profile-tracing experiment.

Magnetoelastic materials undergo changes in their magnetic field when subjected to stress, and therefore suggest themselves as possible transducers in tactile sensors. A material is magnetoelastic if there is a relationship between changes in its internal magnetic moment, changes in the physical forces applied to, or by, it and changes in its physical length (Vranish, Mitchell, and DeMoyer 1982). This method of tactile transduction has seen little development in robotics, although there are several papers on the subject.

The Gould Research Centre has done some investigations using a nickel-based core wrapped with wire in a manner similar to that of a transformer, having primary and secondary windings (Checinski and Agrawal 1986). The direction of the vector of magnetic induction affects the secondary magnetic flux and hence the secondary voltage generated. The amount of secondary voltage is directly related to the amount of applied force, thus providing the functionality of a tactile sensor. The experimental single-element sensor has wide dynamic range, a linear response, and hysteresis of about 1%. Having no moving parts, the sensor is also robust and is able to withstand considerable overload. Another important feature is that the temperature error is low. This was an exploratory design only, however, and has to be incorporated into an array to determine its capabilities more fully.

Another magnetoelastic tactile sensor, functioning rather like a strain gauge, has been constructed using a new material called Metglas (Mitchell and Vranish 1985). This is made as a thin ribbon. In the sensor, it is bonded to a specimen backing, and a coil is wound around the composite. The coil generates a field which encloses the Metglas. When the composite is stressed, the Metglas changes its susceptibility, which is measured as a change in inductance of the coil. Experiments showed that the sensor is two orders of magnitude more sensitive than a conventional strain gauge, and has good temperature stability. A problem inherent in the design is the bonding of the Metglas strip to the backing specimen. A perfect bonding between the two would restrict the rotation of the Metglas magnetic domain, and the sensor would not work. Despite its other advantages, the inevitable compromise on bonding will be a problem.

At North Carolina State University, a magnetoelastic tactile array of 256 elements with 2.5-mm center-to-center spacing has been successfully built (Luo, Wang, and Liu 1986). The design is similar to that of Checinski and Agrawal, except that the core material is Vitrovac 4040, based on nickel and iron. The sensing system incorporates a microprocessor, bandpass filter, analog-to-digital conversion, and video display. Tactile image processing can be performed by the microprocessor. This sensor is highly linear over 0–50 g (0–0.49 N) loads, with a slight tailing off up to 70 g (0.687 N). Hysteresis is low, and the sensor is temperature stable. No figures are given for durability cycle times, although the inherent robustness of a design requiring no moving parts or dependency upon elastomer properties suggests it is rugged.

Vranish, who has been investigating magnetoelastic materials for some time, has designed a magnetoresistive tactile sensor (Vranish 1986a). A material which is magnetoresistive undergoes a change in electrical resistance when subjected to a magnetic field. The proposed design has 8×8 elements of the magnetoresistive material Permalloy (81-19 Ni-Fe) etched onto a suitable substrate with connectors to form an array. Above this is a thin rubber layer on top of which is a Mylar film with copper conducting wires on it. These wires provide the magnetic field which will affect the Permalloy resistance underneath. Covering the whole structure is a sheet of rubber which forms the outer surface of the sensor array. Contacting objects cause the copper and Mylar to be displaced, thereby altering the magnetic field strength around the Permalloy elements. This field strength at the Permalloy is inversely proportional to the distance between Permalloy element and flat wire above it. A linear response is achieved. The elements are 2.5 mm apart over a 25-mm^2 surface.

The sensor has been built, and theoretical predictions suggest that it will be able to detect depressions as little as 0.025 mm, with a dynamic range over 30–300 Pa. Durability also seems reasonable, and magnetic shielding is not required—a point the other researchers do not mention. Vranish states that the sensor can be made spatially denser, and the dynamic range can be improved upon also.

One other design proposed by Vranish is for a magnetoinductive tactile array with 0.5-mm spacing and 8 bit/tactel resolution. The paper design for this sensor and its theoretical performance are given in detail in Vranish (1986b).

A major digression from the approach of most researchers in tactile sensing was taken by a team at Bell Labs, New Jersey. This group asserts that normal force sensing is not the most important parameter to be measured if tactile sensors are to be fully utilized; they believe that local shear and torque are of more use (Hackwood, Beni, and Nelson 1986). This is because they feel that tactile sensors are best used for manipulative tasks where the dynamics of gripper-stimulus interaction are of prime importance. This is opposed to most current approaches which use tactile sensors for shape recognition. To illustrate this, they designed and built a tactile array sensor to measure shear and torque as well as normal force.

Each element in the array has a magnetic dipole embedded in an elastic medium which rests on a substrate containing magnetoresistive detectors. As applied forces deform the elastic material, the dipoles are displaced, producing a change in the surrounding area's magnetic field. Magnetoresistors detect this change and produce an electrical signal which can then be measured. The configuration of the magnetoresistors depends on the components of the force and torque to be measured; the shear and torque components are the only ones used in this sensor. An example of this array sensor was built with a 7×7 matrix, this was for illustration only, as the size is determined by fabrication criteria; element sizes as small as 0.5 mm are possible. No hysteresis was observed, and sensitivity was in the range 1 – 100 g (0.0098 to 0.98 N) but the particular force sensitivity required can be achieved by changing the elastic medium.

Magnetic sensors have only had limited exploitation in robotics. Magnetoelastic transducers have a wide dynamic range, little hysteresis, basically linear responses, and are robust. Shear and torque as well as normal forces can be sensed. Disadvantages are susceptibility to stray fields and noise, although filtering circuits can be incorporated. The choice of suitable materials is narrow. Generally, these sensors deserve more attention.

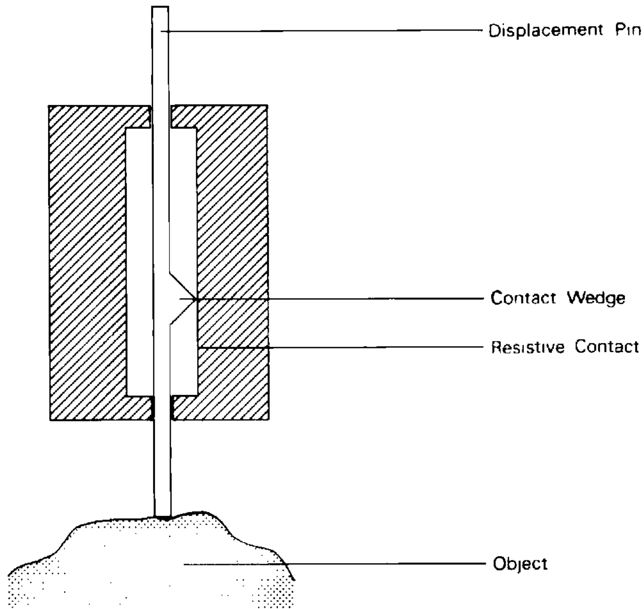
2.2.5. Mechanical Transduction Methods

Some sensors rely on a mechanical displacement caused by an applied force. The simplest example is a spring-loaded switch giving on/off contact readings. A linear potentiometer provides a graded scale of deflection, and the output can be considered in terms of either force or linear displacement. An example of such a sensor used to detect travel in the z axis (central approach axis) of a robot gripper is mentioned in Warnecke and Haaf (1981). Other devices measure angular displacement, such as optical shaft encoders, angular potentiometers, etc.

A common example of mechanical displacement in simple touch sensors is the movement of a linear probe. Presern, Dacar, and Spegel (1981) designed a three-degrees-of-freedom probe for arc welding applications. It is intended for seam tracking, the robot moving along an ideal trajectory and the probe giving (x, y, z) data on the actual seam position. The sensor consists of a measuring needle placed inside a tube, displacement along this z axis being measured by a linear variable differential transformer. A small servomotor is used to advance and retract the needle when searching for contact. Movement in the xy plane is sensed by the displacement of the plates of a capacitor which are attached to the needle. The sensor has a fast response time due to its small mass, low friction forces on the needle movement due to xy position sensing through capacitance, and high adaptability in the z direction via the servomotor. One noted problem, however, was ambient noise affecting the capacitor readings, a point mentioned in section 2.2.3.

Another probe-based sensor was developed at the University of Wollongong, Australia (Russell 1985a). The probe, or whisker, is made from an 11-cm syringe needle and is affixed to a ball-and-socket joint allowing horizontal and vertical pivoting. Movement of the whisker is achieved by two loudspeaker voice coils and push rods. A switch impact sensor is mounted on the whisker. Movement control and recording and processing of contact data are performed by a microcomputer. Output ports from the microcomputer are connected to the voice coils via digital-to-analog

Fig. 8. Mechanical transducer: a linear potentiometer.



converters; the signals are amplified before driving the speakers and hence cause whisker movement.

The whisker assembly was mounted on the end of a robot manipulator and used in an object recognition system. The robot first carried out a raster scan of the work area and then the whisker was used to perform edge tracking of any objects encountered. The test objects used were chess pieces, since they are known and similar shapes. The raw outlines were noisy but usable after averaging. The significant features of this approach are simplicity, low data volume, and the low inertia yet high sensitivity of the whisker. The robot carries out the coarse movements, and the whisker is used for the fine-detail tracing operations.

Some other novel mechanical devices detect the sound generated by movement against the sensor surface. Such a sensor developed at the University of Karlsruhe, West Germany, uses a microphone containing a piezocrystal. Microphones are mounted on opposing jaws of a sensory gripper, so the signals generated by the sensor are the result of actions within the gripping area. Noise from the gripper motor is filtered out by a rubber material covering the crystal. Slip can also be detected by this sensor (Dillman 1982).

Figure 8 illustrates a mechanically based sensor. Many of the devices detailed in other sections could technically be described as mechanical sensors (for example, Sato, Heginbotham, and Pugh 1986), but they have been included elsewhere to illustrate an alternative design within a transduction class.

2.2.6. Optical Transduction Methods

The development of optical fiber technology and solid-state cameras has led to some interesting new tactile sensor designs. The capability for high-spatial-resolution images, freedom from electrical interference, and ease of separation of sensor from processing electronics are some of the attractions of incorporating optical transduction methods into tactile sensors.

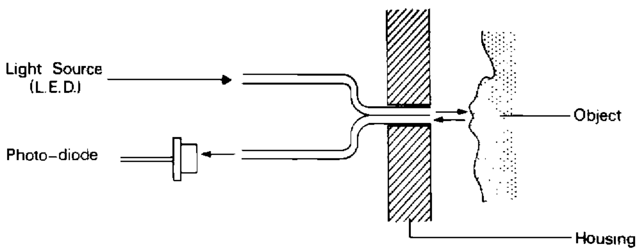
One of the few commercially available tactile sensors uses electrooptical transduction with mechanical displacement (Rebman and Morris 1986). The Lord Corporation market three versions: the LTS100, LTS200, and LTS300T. The first two sensors use an optomechanical transduction method. In these two designs, the sensor surface is made of a compliant material which has on its underside a grid of elongated portions forming pins. When the surface receives an applied force, the pins on the underside undergo a mechanical deflection normal to the surface. Each pin is moved into the light path of a photoemitter-receiver pair. The amount of movement determines the amount of light reaching the photoreceiver; this is digitized and represents the amount of force applied at that site.

The LTS-100 sensor is an 8×8 array with 7.62-mm center-to-center spacing and so has very poor spatial resolution. Each deflection increment represents 3.18 g (0.031 N), facilitating a dynamic range of 0–681 (6.682 N). The sensor was connected to a Motorola 68000 processor which analyzed the tactile image and provided location and orientation data to a computer system. This was used successfully in the assembly of a flexible diaphragm and plastic cap.

The LTS-200 sensor has an array of 10×16 tactels spaced 1.8 mm apart, but only 4 bits of data per element. This design is robust, but each tactel must be individually calibrated, and its ultimate resolution is limited by the very nature of its transduction mechanism. It is, however, one of the few commercially available tactile sensor arrays.

The third Lord Corporation sensor, the LTS300T, is

Fig. 9. Optical tactile element: surface reflectance.



a tabletop pad sensor of 80 × 80 elements with 0.203-cm site-to-site spacing. Each site has 8 bits of data associated with it, which may be transferred to a computer system via a parallel port. However, this sensor uses conductive elastomer transduction (Lord Corporation publicity leaflet).

The University of Arkansas College of Engineering is pursuing the commercialization of an electrooptical tactile sensor. A publicity bulletin shows a linear response for the sensor, but does not describe its workings. It is capable of detecting a surface deflection of 0.00001 inch.

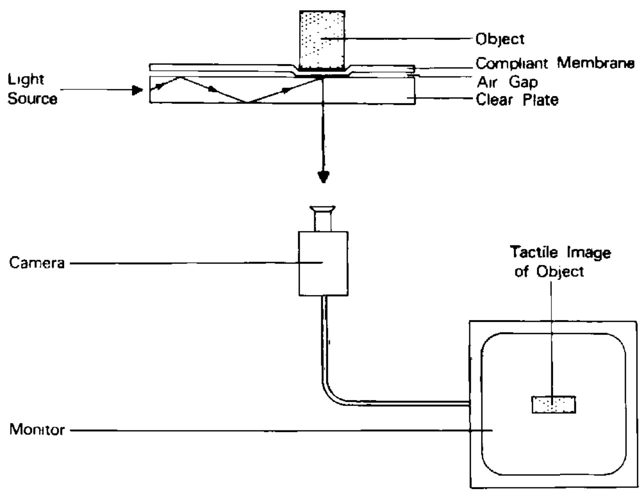
A simple but effective sensor using optical fibers is described by Crosnier from Souriau et Cie, France (Crosnier 1986). This works by detecting the amount of reflected light from an illuminated object. Light from a light-emitting diode (LED) is passed down a fiber-optic cable to illuminate any proximal objects. A second cable picks up any reflected light from illuminated objects within a detection zone and directs it onto a photodiode. This simple technique was built into a finger. The finger can sense contacts perpendicular to the finger axis, radially, and also axial contact at the fingertip. Radial contact is detected using a mobile ring around the finger. Movement of the ring caused by contact is sensed using fiber-optic transmitter/receiver pairs as described above. Fingertip contact is also measured this way. Six fiber-optic cable pairs are evenly spaced around the mobile ring. A contact force of 10 g (0.098 N) is the threshold for detection. Three of these fingers were built and incorporated into a gripping system based upon contact data from the sensors. Figure 9 illustrates this transduction method.

A planar tactile array sensor using a similar technique for contact sensing is described in Schneiter and Sheridan (1984). Fiber-optic transmitter/receiver pairs are arranged to form a matrix of sensing sites. On top of the fiber ends is a layer of clear Sylgard elastomer topped with a white silicon rubber layer. The amount of light reflected from the silicon layer is determined by its height above the fiber-optic cable ends. Any contacting objects will press into this elastomer and alter its height. Variations in the light intensity therefore indicate the presence and shape of the contact. The fiber receivers are fed into a camera and then digitized. A computer then selects one pixel per fiber that is most representative of the intensity within that fiber. The prototype has a 34 × 35 fiber matrix on an area of 0.19 in^2. The dynamic range is about 18 : 1, and the reaction time is 1/30 s, the camera frame rate. A second design is suggested using each fiber as both receiver and transmitter, and is much easier to build. The resolution of the sensor has to be traded off with the layer thickness, but high resolution is easily attainable. The transparent Sylgard layer fatigues after a few hundred cycles, but hysteresis is not a problem.

A variation on the reflectivity-based sensor is described in Collins and Hoover (1987). This sensor consists of an optically sealed chamber, one side of which is an elastic reflective surface. Light directed onto the elastic surface is reflected onto an optical RAM. A grid pattern is placed on the reflective surface, which is deformed by applied force. The image received by the optical RAM is thus a function of the stimulus applied to the sensor. A prototype has over 5000 tactels/mm^2. Response is linear.

A novel fiber-optic tactile sensor is described in Schoenwald, Thiele, and Gjellum (1987). This design uses the phenomenon of light being radiated normal to the axis of an optic fiber at places where there are inhomogeneities in the fiber. The sensor consists of four parallel, evenly spaced optic fibers mounted on a substrate. Another array is mounted on top of these, but oriented orthogonally to form a grid pattern. The fibers are surface abraded at the grid junctions. The rows can be separated from the columns by a clear elastomer or by an elastomer with holes at the junctions between fibers. The rows are sequentially illuminated by LEDs, and the columns are connected to photodiodes, which are sequentially scanned during the time that a single row fiber is illuminated. An efficient scanning mechanism is thus achieved. When a row fiber is excited by an LED, light is radiated from the places where it was abraded. By reciprocity, ra-

Fig. 10. Optical tactile element: pressure intensity to light intensity transduction.



diated light from the row fiber incident on the corresponding column fiber will be coupled into that column fiber along its axis. The light from this coupling is detected by the photodiode. Force applied to the sensor surface compresses the elastomer and increases the coupling between fibers by decreasing their separation. A prototype has been built and is under evaluation.

Several designs using another optical transduction technique show great promise. Such sensors use the properties of reflection between media of different refractive index (Fig. 10). The sensor comprises a clear plate illuminated on its edge by a light source, and an opaque elastic membrane above the face of the plate. The plate has a higher refractive index than the air surrounding it, and the membrane has a higher refractive index than both air and the clear plate. The light directed into the plate remains within it due to total internal reflection. This occurs because the plate is surrounded by air having a lower refractive index than the plate. When an object is placed on the rubber membrane, the rubber is brought into contact with the plate. At the places where this happens, light is diffusely reflected out of the lower face of the plate, because the rubber has a higher refractive index than the plate. When viewed from below, bright areas show up that correspond to the shape and position of a contacting object. The intensity of the bright areas is proportional to the amount of force being applied.

Begej, at the University of Massachusetts at Amherst, describes an array sensor built around this technique (Begej 1984). He constructed a tactile "table" with the membrane above the plate and a 128×128 charge injection device camera below to capture images. This gave a tactile element density of 1500 tactels/cm^2. He investigated various membrane types and used an opaque rubber layer on top of a microtextured membrane. For the same total thickness, a larger texture enabled greater depths to be sensed, but in less detail. The transducer membranes used were white plastic and parallel rows of Lycra fibers bonded to a tape backing. The covering membranes tried were black plastic sheet, balloon rubber sheet, and neoprene sheet. A more compact version using fiber-optic cables to transmit the image to a remote camera was also constructed. This design has a tactile element density of 54 tactels/cm^2. The response was nonlinear but monotonic, with some hysteresis. Creep was acceptable within a 10-s time interval. The Begej Corporation of Littleton, Colorado, is now marketing a fingertip-shaped sensor.

King and White, working at the University of California, Berkeley, also investigated suitable skin materials for an optical tactile sensor (King and White 1985). They found that neoprene rubber exhibits significantly less hysteresis than both latex and silicon rubber. They experimented with hemispheric, pyramidal, and smooth surface textures. All gave a response that had a linear section, and pyramidal elements had the widest range of response.

They also examined tactile elements for measuring shear, tensile stress, and torque. The most versatile element was based on detecting the compression of a rubber ring resting on the clear plate surface. The element is prestressed to create a response without an applied force, so that tensile forces will produce a change in the sensor output. Shear force is measured by determining the difference in response between one side of the ring and the other. Torque can be detected by marking the ring with a pattern and tracking the rotation of that pattern. A prototye element has been built and gives promising results.

King and White suggest a variation on the propagation of light out of a nonhomogeneous optic fiber, an earlier reference to this technique than Schoenwald et al. They also built an optical tactile sensor for mounting on a robot gripper using a MicronEye optic sensor for digitizing the image. Associated electronics transfer the data into a computer. Normal-force values are computed using a look-up table, and shear force is computed by finding the centers of each illuminated area and comparing their locations to those for the unstressed elements.

A Japanese team have constructed a tactile sensor using the optical reflection technique. They direct the image onto an array of discrete phototransistors (Tanie et al. 1986). This is a tabletop design with a strongly textured membrane. The spatial resolution of this design is low because of the phototransistor arrangement. There are 16×32 elements with 3.5-mm center-to-center spacing.

The design under development at the University College of Wales, Aberystwyth, uses solid-state camera technology (Mott, Lee, and Nicholls 1986). A charge-coupled device (CCD) imaging array is incorporated into the body of a robot gripper finger, and the gripping face of the finger contains the membrane and illuminated plate arrangement. Via a mirror and lens, the image from the plate is directed onto the CCD array. A cable running from the finger connects the CCD array to an electronics module. This generates drive signals to the CCD array, performs local image processing, and provides digital-to-analog conversion to give a composite video output signal. The module also has a bidirectional parallel port, so that the "smart" sensor can be connected to another computer. Two fingers are controlled by a single module. The images are only 64×64 tactels, but this is a feature of the electronics module and could be expanded up to the resolution of the 144×208 element CCD array. Even so, the spatial resolution of this version is over 1000 tactels/cm^2.

A commercial version has now been developed without a local processing unit and producing solely a video output, which has an active area of 2.3 cm^2. This gives a spatial resolution of over 28,000 tactels/cm^2 when used with a 256×256 framestore. This version is described in McClelland (1987).

Another sensor using this transduction technique has been developed at the Electrical Engineering Department of the University of Newcastle-upon-Tyne, UK (Ghani 1988). It is the result of collaborative work in tactile sensing as part of European Esprit Project 278, and in conjunction with Joyce-Loebl it is now commercially available. This sensor directs the optical tactile image onto a CCD array, and a video output is produced. One version of the sensor has been integrated into a robot gripper finger which is able to rotate the sensing pad on the fingertip, thereby enabling rotational grasp errors to be corrected without moving the whole manipulator.

The advantages of this technique are simplicity, very high resolution, freedom from electrical interference, low interconnection and cabling requirements, and ease of remote processing. The video output from these designs enables straightforward connection to existing image processing systems.

2.2.7. Other Designs

The main categories of tactile sensor have been examined in the previous sections. There are several other designs which deserve mention but which do not clearly fit into the previous categories.

A force sensor using pulse-echo ranging is described in Grahn and Astle (1986). This sensor consists of a layer of silicon rubber below which is a layer of the piezoelectric material PVF_2. The PVF_2 has electrodes on its upper and lower surfaces, forming the tactels, and is mounted on a substrate. Objects touching the sensor deform the silicon rubber layer. The tactels are subjected to 5-V, 200-ns-wide excitation pulses which, by the reverse piezoelectric effect, deform them. This deformation produces ultrasonic pulses which reflect off the upper surface of the silicon rubber back to the transmitting tactels, which then act as receivers. The time taken to receive the echo is linearly proportional to the amount of deformation of the rubber. A 12-element array was fabricated, and the sensor exhibited a 2000 : 1 dynamic range from 1.034 to 2068.43 kPa (0.15 to 300 psi). A significant point about this sensor is that the response time is equal to the ultrasonic pulse transit time, around 5 μs. Spatial resolution of forces 0.5 mm apart is also possible. Ultrasonic pulse-echo ranging using PVF_2 is also incorporated in the sensing system of Dario at Pisa (Dario et al. 1987).

Transensory Devices Inc. produce a commercially available silicon strain gauge tactile sensor (Kowalski 1985). Each sensing element consists of a silicon mesa (or box) on a silicon diaphragm. The mesa is capped with a thin plastic layer, and then an elastomer layer covers the entire sensor, which is mounted on a glass substrate. All the interface circuitry, the mesa, and the diaphragm are manufactured from a single piece of silicon. The output from the sensor is an analog voltage that is proportional to applied force. An advantage of this design is that the function of the elastomer cover is protective rather than sensory. It can be optimized for its mechanical properties rather than its electrical properties, the force transduction being carried out by the silicon construction. A single element and a 3×3 sensor with 2-mm center-to-center spacing have been built. The output is linear with a dynamic range of 100:1 over a 10–1000 g (0.098–9.8 N) load. The sensor is rather fragile, but the solid-state transduction technique offers scope for sophisticated designs.

A unique design is under test at the University of Florida (Patterson and Nevill 1986), known as the induced vibration touch sensor. The sensor consists of two layers of PVF_2 piezoelectric film covered with a ridged silicon rubber skin. The PVF_2 layers are sensitive in orthogonal axes. The unusual aspect of this sensor is that it detects relative motion between the sensor and a contacting object. The motion between sensor and touching object produces vibrations that induce a voltage in each sensing layer. The output from each layer is related to the speed, orientation, and shape of the object in contact. The design is dynamic, whereas most other designs are inherently static. Various experiments were conducted, and successful recognition of cylinders and spheres differing by $\frac{1}{16}$ inch in diameter was achieved.

The final two sensors both detect thermal properties through contact with an object. Russell at Wollongong University, Australia, has developed a thermal sensor array of 2×10 elements spaced 2.5 mm apart (Russell 1985b). Each element consists of a heat source (a power transistor) soldered to a copper block. The copper has a known rate of thermal conductivity and spreads the heat from the transistor evenly across its bulk. A thermistor measures the heat in the copper, and a feedback circuit is used to maintain a constant temperature. A 3-mm outer layer of silicon rubber containing another thermistor acts as the contacting surface. The temperature drop caused by the flow of heat into an object is measured by the thermistor in the outer layer. In experiments, the sensor was able to distinguish between aluminium, wax, cork, and plastic foam. Although the response time is about 3 s, images representing the material constitution of touching objects provide a novel form of tactile data.

A combined force and temperature sensing design is proposed by Jeswiet and Nshama and is to be mounted on a robot gripper (Jeswiet and Nshama 1986). Manganin (an alloy of manganese with copper and nickel) is used as a pressure sensor and titanium as a temperature sensor. Manganin is sensitive to pressure changes but not to temperature changes, while the reverse is true for titanium. Small deposits of each material are laid out in a matrix form as a ceramic layer with a micron thick layer of silica coated over the top. The silica protects the sensor surface and prevents any electrical signal loss. The resistance through each site is dependent upon pressure and temperature for manganin and titanium respectively. This sensor has not yet been constructed, and it will be interesting to see experimental results.

Papers on passive and active force sensors, tactile array sensors, tactile transducers, and ultrasonic sensors are collected in Pugh (1986b). Some of these papers are discussed in this survey. A companion volume, concerning vision sensors, is Pugh (1986a).

2.3. Summary

This section has dealt with the major categories of tactile sensors based upon the transduction method used. It is clear that there are opportunities for innovative designs, since tactile sensing has only seen significant research activities since the early 1980s and there are very few commercially available sensors. Below are summarized the main advantages and disadvantages of each transduction method and some typical designs noted.

2.3.1. Resistive and Conductive

Advantages:

- Wide dynamic range
- Durability
- Good overload tolerance
- Compatibility with integrated circuitry, particularly VLSI

Disadvantages:

- Hysteresis in some designs
- Elastomer needs to be optimized for both mechanical and electrical properties
- Limited spatial resolution compared to vision sensors
- Large numbers of wires may have to be brought away from the sensor
- Monotonic response but often not linear

Typical designs: Robertson and Walkden (1986), Raibert (1984), an extension of Hillis (1982).

2.3.2. Piezoelectric and Pyroelectric Effects

Advantages

- Wide dynamic range
- Durability
- Good mechanical properties of piezo/pyroelectric materials
- Temperature as well as force sensing capability

Disadvantages:

- Difficulty of separating piezoelectric from pyroelectric effects
- Inherently dynamic: output decays to zero for constant load
- Difficulty of scanning elements
- Good solutions are complex

Typical Designs: Dario et al. (1984)

2.3.3. Capacitive Techniques

Advantages:

- Wide dynamic range
- Linear response
- Robust

Disadvantages:

- Susceptible to noise
- Some dielectrics are temperature sensitive
- Capacitance decreases with physical size, ultimately limiting spatial resolution

Typical Designs: Siegel, Drucker, and Garabieta (1987)

2.3.4. Magnetic Transduction Methods

Mechanical Displacement

Advantages:

- Wide dynamic range
- Large displacements possible
- Simple

Disadvantages:

- Poor spatial resolution
- Mechanical problems when sensing on slopes

Typical designs: Sato, Heginbotham, and Pugh (1986)

Magnetoelastic and Magnetoresistive

Advantages:

- Wide dynamic range
- Low hysteresis
- Linear response
- Robust
- Normal force, shear, and torque capability

Disadvantages:

- Susceptibility to stray fields and noise
- ac circuitry required

Typical designs: Hackwood, Beni, and Nelson (1986), Vranish (1986a)

2.3.5. Mechanical Transduction Methods

Advantages:

- Well-known technology
- Good for probe applications

Disadvantages:

- Complex for array constructions
- Limited spatial resolution

Typical designs: Ressel (1985a)

2.3.6. Optical Transduction Methods

Advantages:

- Very high resolution
- Compatible with vision sensing technology

No electrical interference problems
Processing electrons can be remote from sensor
Low cabling requirements

Disadvantages

Dependence on elastomer in some designs
Some hysteresis

Typical designs: King and White (1985), Mott, Lee, and Nicholls (1986)

3. Processing Tactile Sensory Data

3.1. Introduction

The literature on tactile sensor data processing reveals that it is an underdeveloped field. There are parallels with developments in the early days of vision processing, with the major objective of many systems being object recognition. Statistical pattern matching of sensed features is common, typically based on parameters such as area, holes, edges, corners, etc. Some experiments also extract position and orientation data from a tactile image. Such experiments have gained their results through the analysis of a single tactile image. However, a few researchers have looked at the utility of active tactile sensing to build three-dimensional surface representations, and in the investigation of sensing texture, hardness, stability, and so on.

The various approaches that researchers have chosen for the processing of tactile data are reviewed below.

3.2. Analysis of Static Tactile Images

Much of the early work in tactile processing was concerned with the analysis of a single tactile image. Recognition of contacting objects by extracting and classifying features in the tactile image was a primary goal. The sensors used were planar arrays of low spatial resolution, typically 8×8 tactels.

One of the earliest accounts of a tactile sensor in use is by Kinoshita, delivered at the Third International Joint Conference on Artificial Intelligence (Kinoshita 1973). He accounted for the site-site spacing of the binary tactels in his calculations, which were based upon the eigenvalues of the digitized pattern. After a learning phase, the program was able to recognize a triangular prism, a square, and a circle. The sensor was mounted on an anthropomorphic hand which grasped the sample object. Later work along these lines is described in Kinoshita (1977).

Also around 1977, another team were using their 8×8 matrix of probes for recognition tasks (Sato, Heginbotham, and Pugh 1986). Their recognition strategy involved extracting contours from the image. The program related the contours to each other, constructing a treelike structure which was then converted into a linear progression. The identification of a part was then a matter of comparing recorded and current progressions. This approach was reasonably fast (0.31 s for obtaining a progression and comparing) but involved considerable computation for high-resolution images.

A simple pattern recognizer for distinguishing features such as pits, spurs, cracks, etc. was developed for use with a 4×4 sensor (Snyder and St. Clair 1978). The processing is straightforward, the first stage being the operation of a region grower to group tactels into regions of high and of low pressure. The second stage is the application of simple predicates to classify the regions picked out in the first stage. The predicates classify regions as one of pit, point, ridge, crack, spur, or edge by using rules concerning the size, location, and pressure type (high or low) or a region. In addition, presence of touch and location and magnitude of center of pressure are calculated. This was one of the earliest attempts to classify the nature of surface features via tactile sensing. Most other examples are conventional object recognition paradigms.

A well-known early paper is Briot (1979), which describes the use of a 10×10 binary sensor in identification tasks. The system identified the face, one of eight, of a known object which was touching the sensor. The program also calculated the object's position and location using the centroid and second moment about the major axis of the region present in the tactile image. For identification of the face, the feature was normalized to make it position and orientation independent. A learning phase of presenting each face 10 times was undergone. The recognition phase consisted of digitization, normalization, calculation of the probability associated with the feature, and finally a decision rule for classification. A stochastic structural technique was adopted. This used three parameters of the image pertaining to its structure, and the classification applied to these only. This approach was very reliable.

Briot incorporated this approach into a manipulator system using a parallel jaw gripper, each jaw having a 5×10 sensor. First, the recognition of a grasped object was attempted, then the robot was directed to move to a location based on the classification. The system was able to identify between a half cylinder and two sizes of parallelopiped, all smaller than the sensor. Although the sensor was spatially coarse (7-mm^2 elements, 5 mm apart), Briot demonstrated the viability of tactile sensing by applying conventional stochastic recognition techniques.

Linguistic pattern recognition was the approach adopted by Chalupa et al. (1982). The boundaries of features in the tactile image were encoded as a modified Freeman chain code (Freeman 1974) and then lowpass filtered for edge noise removal. This "cleaned" chain code was then highpass filtered, leaving only the changes in the boundary, indicating the corners of the feature's boundary. The corners were used as linguistic pattern primitives to form a sentence describing the boundary. This sentence was then parsed using two string grammers, for oval patterns and for angular patterns, respectively. For the angular patterns, parameters such as corner positions, edge lengths, and angle between edges were computed, while centers and symmetry axis were calculated for the oval patterns. These parameters were then used in a semantic analysis stage to classify within each shape category, determining the boundary to be rectangle, square, triangle, circular line, ellipse, etc. This technique was 98% successful in experiments. The linguistic approach is highly structured and therefore offers a sound modular approach. However, it does rely on the input patterns being such that they can be reliably partitioned into primitives.

Another bondary-based method is that of Ozaki et al. (1982). The plane closed curve of a contour can be represented as a chain code, which can be considered as a set of unit-vectors with standard angles $k\alpha$ ($k = 1, 2, \ldots, n$) relative to some base line. The angle α is the chosen angular increment. The curve can then be stored as a unit-vector count histogram with n entries, one per angle. Such a histogram is called the unit-vector distribution (UVD).

The UVD has some interesting properties. If the curve is convex, the UVD can uniquely express the curve, but a concave curve requires the sequence in which the unit-vectors occur as well. The perimeter length can be calculated by the number of UVs in the histogram multiplied by the length of each UV. The UVD is unaffected by translation of a curve within an image, but it is affected by curve rotation. The UVD alone is insufficient to regenerate a curve, since the sequence in which the unit-vectors occur is lost.

The Japanese team use UVDs in a tactile pattern recognition system. First, they record an original pattern of each sample object, recording the contour as a UVD. A second pattern is then made from a deliberately blurred version of the original pattern. This blurred pattern is used in a matching process to identify a pattern obtained from an unknown object. The blurring is used to compensate for digitization errors in the unknown pattern, making the matching process easier. Similarity between each blurred pattern and an unknown pattern is determined by a difference operator. The blurred pattern with the nearest distance to the unknown pattern is taken as the result. If a single blurred pattern cannot be determined, further readings are taken and the process is repeated. Experiments were able to discriminate cylinders and prisms. This method works well for convex curves using a small vector length and a small incremental angle, but the larger these two parameters, the less reliable is the method. It is not suitable for handling concave curves. Such curves would have to be broken into a sequence of curves, the divisions being at the boundaries of the concave and convex parts.

Christ and Sanderson (1982) used a feature set made up of area and normalized first and second moments in their recognition system. A detailed description of moments is presented in Hu (1962). Moments were selected to make the system location and orientation independent. A learning phase of presenting each object 10 times was conducted, then recognition attempted using a decision rule. For each object, the mean and variance of each feature were recorded in the learning phase. Classification of a contacting object involved computing the distance of each measured feature from the mean of each taught feature. This was normalized to the standard deviation. The correct classification was taken to be the nearest distance between observed and taught means, normalized to the standard deviation. The objects involved were meters, tapes, tubes, batteries, and cans, all smaller than the sensor. Out of 50 classifications, 48 were correct. The objects were uncomplicated and diverse, but the experiments demonstrated that simple feature extraction and a straightforward decision rule are of utility. An extension to the moment-based approach, using complex moments, is discussed in Luo and Loh (1987).

The Esprit 278 Project was concerned with both tactile and vision processing (Ghani 1988). The tactile image processing involved digitizing images from a pair of finger-mounted tactile sensors, reducing the image features to a set of typed vectors, and then attempting matching with the aid of geometric constraints. Recognition and location tasks were performed using a purpose-built tactile processor, consisting of an M68000 microprocessor augmented with a TMS32010 digital signal processor. Data generated by this system was passed on to a robot control system.

Some other image processing techniques are used by Muthukrishan et al. in experiments with the Lord Corporation LTS200 sensor (Muthukrishnan et al. 1987). They applied nonlinear median filtering for noise suppression, then thresholded the image using a bimodal histogram to achieve a binary image. For objects less than the sensor size, local gradient operators (the Sobel and Roberts operators) were used to extract edges, and template matching was also carried out. Contour tracing using a variation on a raster tracking method was possible in the images tested. Segmentation and region growing were also experimented with to aid extraction of edges associated with objects greater in size than the sensor. Filtering for tactile sensing is also discussed in Sasiadek and Wojcik (1987). Filtering, thresholding, segmentation, etc., are all techniques commonly found in image processing, particularly vision sensing. A thorough introduction to this subject is available in Ballard and Brown (1982). Clearly, existing image processing techniques have considerable relevance to tactile processing.

An interesting digression from the conventional tactile recognition approach is that of Grimson and Lozano-Pérez (1984). The problems they considered were the identification of a sampled object with respect to a set of known objects, and the calculation of its location relative to the sensor. They do not specify the type of sensor, but assume that a small set of points on the object to be recognized has been collected. For each of these points, the surface normal of the object's surface is calculated. High accuracy is required for the point collection, but some uncertainty is permissible with the surface normals. Their recognition system also requires a geometric object model for each known object.

The recognition process comprises two stages. First, a set of feasible interpretations, consisting of pairing each sensed point with an object surface on a known object, is generated. The second stage is a more complex but rigorous testing of feasible interpretations against the surface equations of each known object. Any inconsistencies will be rejected to yield a match between a known object and the sampled object.

The important aspect of this approach is the first stage, as this exploits local constraints on the sensed points to achieve swift rejection of some of the objects in the taught set. The second stage is computationally expensive, so a preliminary faster testing stage is advantageous. The local constraints used are based on distance, angle, direction, and a triple product calculation. The distance constraint states that the distance between each pair of sensed points must be a possible distance between the faces assigned to those two points. Similarly for angles between surface normals at the paired points and angles between surface normals of the assigned faces. The direction constraint looks for inconsistencies between a vector passing through paired points and a vector between the faces assigned to those two points. Finally, the triple product constraint requires that the sign of the triple product of the measured normals at three points must agree with the sign of the triple product of the corresponding face normals. If all these constraints are satisfied, the few remaining possible interpretations of the sensed data are rigorously tested against the surface equations of the appropriate object models. This should result in a unique classification.

There are several interesting features of this approach. First, the sensing requirements are for a small set of fairly accurate points on the sampled objects. Large numbers of elements on a tactile sensor are unnecessary, but good spatial resolution over a small area is important. Indeed, the sampling could come from a range finding sensor rather than a tactile sensor, and the authors demostrate this in a simple experiment. Second, the surface normal is a useful parameter for recognition constraints and is not often considered in tactile sensing. This method also demonstrates the classic artificial intelligence paradigm of generate and test applied to a practical situation.

All the systems described so far have been concerned with object recognition. This has been the primary goal of static tactile image analysis. However, a few researchers have considered other aspects of tactile sensing. Wolfeld, for example, calculates the slant angle between the sensor plane and the plane of a contacting object (Wolfeld 1981). This was done by simply averaging all the pressure differences between horizontally adjacent sites. After a correction factor the resultant angle was accurate to within 2%. Other people have considered grasp constraints and hand designs. Salisbury carried out a detailed kinematic and force analysis of articulated robot hands to ascertain the best design for stable grasping (Salisbury 1982). He also analyzed the grasp forces in a three-fingered three-degrees-of-freedom gripper to determine features of point, line, and surface contact (Salisbury 1984).

Bajcsy et al. consider the problem of how to grasp an object and specify the theoretical framework required (Bajcsy, McCarthy, and Trinkle 1984). Their approach is similar to that of Salisbury, but they integrate constraints from all three sources: the object to be grasped, the geometry of the hand, and the kinematics of the grasped object.

Fearing and Hollerbach have analyzed the strains and stresses beneath a compliant skin using a linear elastic mathematical model. They concluded that three strain measurements were necessary for determining the location, magnitude, and direction of force for a line contact (Fearing and Hollerbach 1985). They suggest that four sensors with high dynamic range may be sufficient in the planar case for determining force magnitudes and directions. This could be sufficient for distinguishing between vertex and side contact types.

This analytic approach for determining sensor parameters is important for optimum sensor design and use. Cutkosky et al. examined experimentally skin materials for optimizing grasping (Cutkosky, Jourdain, and Wright 1987). They found that treads, grooves, and surface textures substantially improve the consistency of surface friction, and hence grasp security, under moist conditions. Fearing also discusses ridges on the sensor surface and suggests that they increase the strain amplitude by a factor of 4. The sensitivity can thereby be increased by placing sensing elements beneath and between ridges to detect the maximum-amplitude strain peaks. The analytic and empiric approaches thus complement one another, in this case to optimize both grasp surface and sensitivity.

Grasp methods, effects of compliance (in components and grippers), assembly techniques, etc., are all issues of wider significance that are receiving considerable research attention. The reader is referred to Brady et al. (1982) and to IJRR (1988) for further information on these topics.

The approaches examined up to now have concerned the analysis of a single tactile image. The next section examines what has been done with multiple tactile images coupled with position data from the manipulator system.

3.3. Active Tactile Sensing

The previous section looked at recognition of objects through the analysis of a single tactile image. This is essentially a static mode, whereby the sampled object is placed on a sensor or grasped in a tactile gripper and the resultant image examined. It is analogous to much vision processing and uses techniques developed in the visual domain. The static mode of tactile analysis is known as cutaneous sensing and is analogous to human fingertip sensing.

The tactile domain differs from the visual domain in a number of ways, but one major constraint on the utility of a tactile image is that it provides only a localized view of the contacting stimulus. Particularly in gripper-mounted tactile sensors, the active area of the sensor is often small compared to the size of the objects being handled. Certainly, only a small number of faces out of the total on an object will contact a tactile sensor.

A way to improve this situation is to use an active sensing strategy. Instead of a single static image, a number of images are recorded from different parts of the object under examination. The set of such images coupled with three-dimensional position data from the manipulator system can be used to construct a three-dimensional representation of a sampled object. Other parameters about the object, such as texture and hardness, may be sensed in this way. This active approach is termed kinesthesia, and the combination of cutaneous and kinesthetic sensing is called haptic perception. The major examples of such active sensing to date are described below.

Some of the first researchers to recognize the importance of kinesthetic sensing describe their work in Gurfinkel et al. (1974). By using a 3×3 sensor with wide dynamic range, they were able to gather data suitable for input to surface curvature calculations. The classifications used were vertex, spherical surface, plane, cylindrical surface, edge, and curved edge, derived from the readings from a single tactile image. Experiments for recognizing cubes, spheres, cones, etc., were conducted using two sensor arrays, one on each finger of a parallel jaw gripper. This was then extended to active sensing experiments. Models of the above objects were stored, including surface curvatures and details of presence or absence of parallel planes and edges. The recognition strategy consisted of moving the sensor into contact and calculating surface curvature. This was then compared with the object models and a hypothesis about the class of object made. The choice of next direction to move along was based upon the hypothesis made. A hypothesis-verification loop causing a tracing of the object's surface followed, until recognition was achieved.

This piece of work was significant for its time. The authors studied human methods of tactile perception and realized the importance of active sensing as well as static analysis. The hypothesis-verification loop, or generate and test, is a common technique in artificial intelligence and it is unusual to find it in use in robotics in the early 1970s.

The top-down approach of the hypothesis-verification loop is met again in Hillis (1982). He mounted his sensor, described above, on a tendon actuated finger having torque and position feedback. Sample objects were placed on a compliant surface beneath the finger and were touched and pushed to extract data. The sample objects were small industrial fasteners which were smaller than the sensor's active area. These were screws, cotter pins, dowel pins, and washers, all no more than 12 mm. The distinguishing parameters used were aspect ratio to represent global feature shape, local pressure anomalies to represent bumps and depressions, and stability. This latter was determined by lowering the finger onto the sampled object and then monitoring the force required to push it along in various directions.

The hypothesis idea of active sensing is important because data from a single image is often insufficient for recognition. By making a hypothesis and gathering data, then modifying the hypothesis on the basis of new readings, reliable conclusions can be made by an iterative process. Hillis designed his system around this mechanism; if the image obtained was insufficient to extract relevant data, or additional data were required, then further images were gathered until a firm classification could be made. Although successful, the sample objects were all smaller than the sensor and only a simple parameter set was necessary for recognition. However, he demonstrated the feasibility of this approach.

Workers at the University of Pennsylvania are investigating various aspects of tactile sensing, and are advocates of the active approach. Most of their work has been conducted using one of two sensor designs. The Lord Corporation sensor (Rebman and Morris 1986) has been used, in addition to the French finger (Bajcsy and Goldberg 1984).

Using the French finger on an X-Y-Z positioning frame (detailed in Brown 1980), Bajcsy and Goldberg (1984) attempted recognition by tracing. The examined objects were rigid and static. Their surfaces could be linear, curved, convex, or concave. However, all the objects had vertical nonconcave sides. The recognition experiments involved moving the probe around the workspace until contact with an object was made, and then recording the (x, y, z) coordinates of the contact point. The probe was traced over the object's profile and the trajectory recorded. All the contact points were then connected together and the centroid, volume, and second moments were calculated. These parameters were compared against a database of objects, and matchings were attempted. The sample objects were jars, coffee cups, cardboard boxes, etc. Recognition was successful for the dozen objects in the database, and volume calculations were accurate to within 6%. Another tracing experiment, using a one-dimensional sensor at Chuo University, Japan, is described in Kinoshita, Hajika, and Hattori (1983).

Bajcsy carried out some other experiments using active touch with the French finger. Experiments in material hardness evaluation, texture analysis, and surface normal calculation were conducted (Bajcsy 1985). Hardness was sensed by advancing the sensor in 0.25-mm steps toward the material surface, and readings were taken at each increment. The material hardness is gauged from the slope of the curve of sensor reading against increment: the steeper the slope, the harder the material. Hardness of samples of wood, foam, and felt were tested; distinctions were made between these materials. The same experiments were conducted for liquid glue, clay, and wood, each contained in a plastic bag. The clay demonstrated different hysteresis characteristics to the other materials, because it retained its deformed state after the probe was retracted.

Texture detection was carried out by moving the finger slowly along the surface of the material with the sensor just touching the sample. Readings were taken every 5.6 ms as the finger moved along. The fineness of the surface texture was determined by the magnitude of the local variation of the surface, spectral analysis being used to get the frequency of each pressure scale. Felt, cloth, and a wire grid were tested, and acceptable results were obtained. The felt was classified as smooth because the sensor did not have sufficient spatial resolution to detect the small surface variations.

Experiments to evaluate surface normals were also conducted. The direction of the surface normal was calculated using the highest tactel reading together with the global position of the finger.

Later work has focused on issues in exploratory sensing. The Pennsylvanian team has looked at results in psychology concerning the use of the human hand (Klatzky, Bajcsy, and Lederman 1987). The human haptic system combines information from cutaneous (fingertip) sensors, such as pressure, vibration, thermal properties, with information from the kinesthetic system that measures position and movement from muscles, tendons, joints, etc. The parallels between human haptic systems and robotics are introduced in Harmon (1984) and are now being developed for robotic exploratory sensing.

The paradigm discussed in Klatzky et al. (1987) associates specific hand movements with exploratory sensing for three classes of properties: surface (texture, hardness, temperature, etc.), structural (shape, volume, etc.), and functional (part motion, specific functions). These active sensing strategies, known as exploratory procedures, are currently under development. Both one- and two-fingered scenarios are being considered. Part of this work builds on the results of Peter Allen's experiments in combining vision and touch for 3D object recognition (Allen 1984), which are described in depth in Allen (1985).

Stansfield has also experimented in combined vision and tactile sensing and incorporates exploratory procedures into a robotic system for determining object properties and relationships between objects (Stansfield 1987). He uses stereo vision and a Lord Corporation tactile sensor. A frame-based object representation is used for reasoning about features; the slots in the frames are filled with features and primitives. Frames are a well-known artificial intelligence knowledge representation technique, originated by Minsky at MIT (Minsky 1975).

Current work in haptic sensing is very promising and tackles the major problems of active tactile sensing. Particularly, object properties such as hardness, elasticity, and thermal characteristics are being investigated that exploit the capabilities of tactile sensors over other sensory media. Integration of the manipulator system, through kinesthesia, with conventional tactile sensing is a major feature of haptic systems.

Exploratory procedures are also used in a robot workstation for aiding a disabled person (Dario et al. 1987). This workstation incorporates tactile, thermal, and ultrasonic sensors in carrying out manipulative tasks on behalf of a disabled operator. Tasks such as discriminating between three partially filled coffee cups using the sensors were demonstrated. The system was even able to detect the arterial pulse waveform of a human through contact with the subject's wrist. This is a novel application and demonstrates that research activities in industry also have relevance to other application domains.

The University of Massachusetts at Amherst has been conducting tactile sensor research, and sensors designed there have been used in sensing experiments. Overton's sensor was used in various situations (Overton 1984), including relative motion detection and surface reconstruction. Calculating motion between the sensor and an object was done by examining successive tactile images. In a set of experiments, forms of cross-correlation were tried, and then feature matching techniques applied. These latter involved the tracking of centroid, ridges, hole centers, edges, etc., in successive images.

The high-resolution sensor of Begej (Begej 1984) was used by Ellis at Amherst in active touch experiments (Ellis 1984). He investigated sensing the radius of curvature of a contacting edge, and experimented with sensing object deformation. A later paper considers the problem of acquiring tactile data in an efficient manner such that an object can be recognized and its location and orientation determined (Ellis 1987). For an initial analysis, the objects were polygons located on a plane. This work extends the ideas of Grimson and Lozano-Pérez, described above, to resolving situations where multiple valid interpretations of the data occur.

Active sensing, exploratory procedures, and object properties all require an integrated approach to the organization of tactile information. Harmon and Rebman suggested a tactile language with this in mind (Harmon 1984). This language groups object properties into intrinsic types (constant characteristics of objects such as texture, shape, hardness) and extrinsic types (force, location, etc.). The condition, or state, in which an object exists can thus be expressed in terms of strings in a language of these tactile primitive properties. Such strings of object conditions could be used as action goals and so be incorporated into the manipulator control methods.

Some aspects of sensing these properties, and some further classifications of object properties, are presented in Nicholls and Lee (1985). This work led to the development of a tactile-sensing taxonomy (Nicholls 1987). A rule-based taxonomic system was developed which encompasses specifications in three important areas: tactile sensors, data representations, and tactile image features. The main parameters which affect a tactile sensor's performance are explicitly represented, including the spatial arrangement of the tactels, the sensitivity of the device, the compliance of the sensor surface, and the type of data which is transduced (e.g., force, torque, displacement). The specification of the data representation indicates the storage requirements for the unprocessed tactile data to be held in a computer system. The tactile image feature specification is used to identify the common features and properties associated with a tactile image.

The purpose of this taxonomy is to identify, parameterize, and relate to each other some major attributes of tactile sensing. By encoding relationships between the three types of specifications, one can determine, for example, the types of image feature a specified tactile sensor is capable of detecting. The converse query could also be answered. Hence, if the image features that a sample object produces are known, then the system could generate the specifications of all the sensors capable of sensing those features. The development of further parameters for this system and of rules relating specifications to one another is the subject of current research.

4. Conclusion

This survey shows that tactile sensing is still in its early stages of development. Significant effort has gone into designing new sensors, and there are some promising devices in use in research laboratories. Despite the findings of the Harmon survey (Harmon 1982), tactile sensing has not made any significant contribution to real applications in factory systems. Commercial tactile sensors are just becoming available, and there is market potential for low-cost, robust, accurate, and repeatable sensors that can easily be integrated into robot systems. The technology is beginning to mature with the advent of commercial devices, and so it is expected that tactile sensors will be integrated in factory-based robot systems in the near future.

The field of tactile sensor data processing has received less attention than that of tactile sensor designs, with many researchers following techniques proscribed by vision processing research. Little use has been made of the unique information that can be gained from a tactile sensor, such as material and surface description in terms of composition, hardness, temperature, stability, and so on.

Too much emphasis so far has been placed on using tactile sensors for shape recognition, emulating the role of machine vision. While recognition is sometimes necessary, verification of the sensed object and of its location are often more appropriate to industrial problems. Closely allied to this is automated inspection, an underexploited area of tactile sensing. The lack of work in this area is probably due to the low resolution of many sensor designs. However, with recent high-resolution sensor developments, detailed inspection using touch becomes feasible. Parts inspection and grasp verification can be performed from a single tactile image, perhaps even during manipulation.

Latest developments are in the area of active tactile sensing in exploratory situations. This is an important area, since it concerns problems of sensory integration, world modeling, and manipulator control. Determining the types of object properties to be sensed is an aspect of this work, a subject of relevance to all tactile sensing applications.

More attention should be given to the use of dynamic tactile data. Data concerning the interaction between grasped object and robot gripper is important during manipulative tasks. Gripper-mounted tactile sensors can provide information concerning pressure fluctuations, slip, and even shear, as well as grasp orientation and location. More exploitation of tactile sensors in these areas would improve the capabilities of advanced robot systems.

This survey has addressed the main areas of research into tactile sensing technology. It is hoped that the reader will be stimulated by the work reported on here to continue research into this rapidly expanding area of robotics.

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