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Review Article

Tactile sensing for mechatronics—a state of the art survey

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Abstract

In this paper we examine the state of the art in tactile sensing for mechatronics. We define a tactile sensor as a device or system that can measure a given property of an object or contact event through physical contact between the sensor and the object. We consider any property that can be measured through contact, including the shape of an object, texture, temperature, hardness, moisture content, etc.

A comprehensive search of the literature revealed that there was a significant increase in publications on tactile sensing from 1991 onwards. Considerable effort in the 1980s was spent investigating transduction techniques and developing new sensors, whilst emphasis in more recent research has focused on experiments using tactile sensors to perform a variety of tasks.

This paper reports on progress in tactile sensing in the following areas: cutaneous sensors, sensing fingers, soft materials, industrial robot grippers, multifingered hands, probes and whiskers, analysis of sensing devices, haptic perception, processing sensory data and new application areas.

We conclude that the predominant choice of transduction method is piezoelectric, with arrays using resistive or capacitive sensing. We found that increased emphasis on understanding tactile sensing and perception issues has opened up potential for new application areas. The predicted growth in applications in industrial automation has not eventuated. New applications for tactile sensing including surgery, rehabilitation and service robotics, and food processing automation show considerable potential and are now receiving significant levels of research attention.

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1. Introduction

Tactile sensing is the process of determining physical properties and events through contact with objects in the world. We review the current state of the art in tactile sensing and examine the trends, developments and application areas in this interesting and relatively new field.

Tactile sensors offer exciting possibilities for use in mechatronic devices and measuring instruments in many areas of science and engineering. Robotics and industrial automation are the application areas that have generated the most interest because contact interactions are a fundamental feature of any physical manipulation system. However, there are many other potential application areas including agriculture, food processing, medicine, dentistry, entertainment, and future domestic and service industries. This literature survey considers only papers with direct relevance for artificial or automated tactile sensing through contact between objects and sensors. Thus we will not consider force sensors or other such seemingly related devices except where they are particularly relevant to tactile problems.

Significant previous surveys of tactile sensing were carried out by Harmon in 1984 [1], Nicholls and Lee in 1989 [2] and Nicholls in 1992 [3]. In this paper, we build on those surveys by reviewing the literature of the 1990s. Starting from the earlier surveys we cover the newer material and thus provide entry points for researchers who wish to work in this field. We also assess the likely developments and research motivations for the near future.

2. The nature of tactile sensing

We define a tactile sensor as *a device or system that can measure a given property of an object or contact event through physical contact between the sensor and the object*. Some previous definitions have assumed that tactile properties must involve force and a number of early tactile sensors were based on strain gauges or other force sensing arrangements for normal and/or shear stresses. However, we reject that narrow definition and accept any property that is measured through contact, including the shape of an object, texture, temperature, hardness, moisture content, etc.

Although most would agree that tactile sensing is essentially a spatially distributed process, much of the literature describes devices and applications based on localised sensing. Many sensory devices have been developed in terms of tactile sensing points, pads or surfaces. The objective of such work is the production of robust and reliable locally discrete devices, e.g., tactile sensors mounted on the gripping surface of a robot end-effector. A more ambitious, related objective is to develop a fully distributed tactile 'skin'.

Another approach views tactile sensing as an integral part of manipulation. In this approach, the joint angles of a robot arm or finger are often combined with surface normals detected via a finger mounted tactile sensor to construct a 3D representation of a surface by following its contours. Research in this endeavour concerns the role of manipulators, often multifingered robot grippers, whose kinaesthetic and kinematic aspects are controlled and coordinated with the contact events taking placing during manipulation. This very integrated approach draws inspiration from observations of dextrous behaviour in the human system.

3. The growth of tactile sensing

Tactile sensing began to develop in the 1970s but Nicholls and Lee [2] report only five papers in that decade. The surveys of Harmon [4] and of Nicholls and Lee [2] both show a wide diversity in the types of sensing device that were invented and developed in the 1980s. New transduction techniques were developed and a large number of experimental devices and prototypes were built and reported in the literature. However, despite repeated suggestions in many papers regarding the potential importance of tactile sensing to industrial automation and other application areas, the literature reported very few applications beyond the experimental prototype stage and hardly any in serious regular use. We will consider reasons for this slow commercial exploitation in industrial applications and assess the chances for future development. First we examine the growth rates of the literature in this field.

Using bibliographic searching tools we have examined a large number of scientific databases and have collated numerical and qualitative results. Figure 1 presents the search data in terms of numbers of journal articles published each year containing the words ‘tactile sensor/sensing’ in the title, key words or abstract, from 1981 to the present.

Two curves are shown—one is the tactile technology literature and the other is medical or physiological material that relates human tactile sensitivity and other properties of the human tactile system to various medical conditions. These medical papers were separated out as they are not relevant to the technology or use of tactile sensing. Figure 1 shows that around 1991 a marked increase in the publishing rate occurred (to more than double) in both scientific/engineering and medical areas.

In a separate examination of databases of conference papers we found a similar story with an average rate of publications on tactile sensing of about 6 per year up to 1990 and an average of over 12 per year after 1990. The earlier inflection point is in accord with the tendency of journal articles to lag conference presentations.

It is noticeable that the absolute numbers of publications in tactile sensing are not high when compared with other sensing technologies. For example, by searching on keywords ‘computer/machine vision’ (which is known to capture just a subset of the literature) over the same periods as above we find an average of about 120 journal articles per year with an average of over 250 total articles per year over the last four years. This order of magnitude increase over tactile sensing reflects both the maturity of the computer vision field and the burgeoning applications of the technology.

4. On sensing modalities

There are five main sensing modalities—sight, sound, smell, taste and touch. It is instructive briefly to compare them to gain insight into the development of tactile sensing.

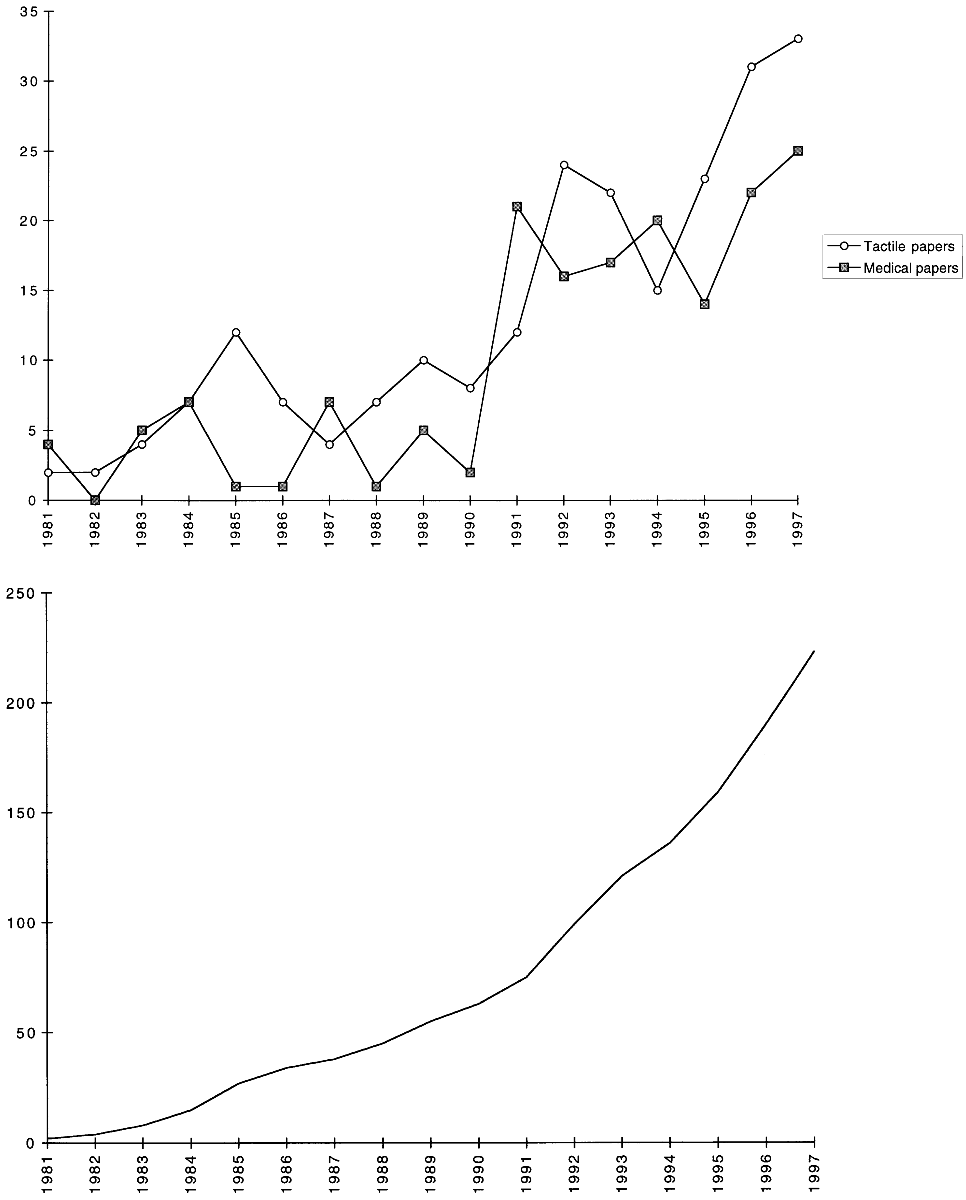

Fig. 1. (a) Journal paper count per year; (b) Cumulative count of tactile papers.

Computer vision systems are now commercially available and widely used for industrial inspection, recognition, monitoring and many other application areas. Similarly, for audio systems; many kinds of audio processing systems are available and there exists a long and substantial literature on the mathematics and technologies of signal processing. Human speech analysis and speech recognition are currently very active research areas and have identified a wide range of applications. Even the senses of smell and taste have their electronic analogies. Devices known as electronic noses are now readily available for the detection of a range of molecules, and chemical tests can be implemented to automatically analyse across particular spectrums in a simulation of taste.

Why then does the sense of touch seem to be so neglected? We do have a history of research in tactile sensing, but it is nowhere near as large in volume or as well developed as in the other sensory modalities. There seem to be several reasons for this apparent neglect. Drawing on the human analogy we see some of the difficulties:

- No localised sensory organ: unlike sight and hearing, the sense of touch has no single sensory organ but operates throughout the skin as a distributed and diffuse process. The transduction of tactile signals is distributed over a much wider area than in a single localised sensory organ, such as eyes and ears. The simulation of this through the creation of an artificial tactile skin is a much more difficult task than the development of discrete sensing devices.
- Complex sensing: tactile sensing through the skin is not a simple transduction of one physical property into an electronic signal. Touch takes many forms and includes the detection of shape, texture, friction, force, pain, temperature and many other related physical properties. It is not yet very well understood how these different aspects of the tactile phenomena are related and how they are processed by the nervous system. Consequently, it is not easy to find suitable technological analogies in science or engineering.
- Difficult to imitate: unlike sight and sound which are well defined physical quantities we do not know what are the best measures to adopt for a tactile sensor. A whole range of physical properties can be transduced and used as tactile signals, but it is unclear as to which is the most appropriate for applications and which should be developed further. In comparison, computer vision research is now mainly concerned with images and their understanding and interpretation, not with developing new cameras and optics. Because the capture of visual data is a solved problem researchers do not have to worry about such low level issues. Tactile sensing has not yet reached this point: we are still concerned with the fundamentals of data capture.

Considering these difficulties, it is encouraging that so much has already been achieved and so many different kinds of tactile sensor are available for experimentation and further development. In fact, if we consider tactile sensing in its most primitive form, i.e., simple contact sensing using a switch for presence or absence of an object, then we see that it is not neglected at all and is used in all kinds of situations such as in machinery, vehicles and safety systems. We refer to single binary devices as 'spatial switches' and, as is usual, we will exclude them from our survey and concentrate on more advanced sensing, involving scalar and array variables.

The lack of any widespread application of tactile sensing is partly due to the difficulties mentioned above and also to the lack of availability of commercial sensors with suitable configurations and characteristics. Nevertheless, we see new areas of application opening up in the future which will capitalise on those aspects provided by tactile sensing that are missing in other sensory modalities.

5. The state of the art in 1990

After a decade of experimentation and device development, the surveys of tactile sensing published around 1990, e.g., Nicholls and Lee [2], report on a range of sensors that can detect object shape, size, presence, position, forces and temperature. Very few examples of sensors that could detect surface texture, hardness or consistency were identified. Most of the devices were either of the scalar single-point contact variety or were linear or rectangular arrays of sensing elements. The main transduction methods identified were the following: Resistance and Conductance, Capacitance, Piezoelectric and Pyroelectric, Magnetic, Magnetoelectric, Mechanical, Optical, Ultrasonic, and Strain gauges.

The processing of tactile signals mainly centred on image processing techniques, derived from computer vision research and applied to static images from array sensors. Some statistical methods were reported for the extraction and recognition of features. Segmentation methods using edge extraction, thresholding, filtering and boundary growing were all employed. Geometric measures and the method of moments were also popular. However, the importance of dynamic events was recognised and sensors were developed for detecting stress changes, slip and other temporal contact events.

The detection of certain material properties, such as hardness and surface texture, were still problem areas for tactile sensing and had not been effectively solved.

Following the pattern in active vision research, the ideas of active tactile sensing only emerged after much work on static data had been completed. Active control was more rapidly recognised as important for the tactile domain. Haptic perception and the role of kinaesthetic information were being investigated and exploratory procedures for tactile property extraction were being developed. Contributions from physiology, psychophysics and neuroscience were giving valuable insight into the nature of human tactile perception.

Nearly all the cited papers dealt with experimental developments and very few commercial quality finished products were available. Despite industrial robotics often being cited as the major application area, additional areas were being proposed for the exploitation of the technology. For example, robotics intended for unstructured, real world applications such as in medicine, exploration and hazardous environments were becoming increasingly represented in the literature.

In our review below, we consider the progress made to early 1998.

6. A taxonomy for the recent tactile sensing literature

It is useful to structure the various contributions from the literature into some form of classification scheme. We identified a primary interest area for each paper and used these to group the material into natural clusters. The primary interest areas are:

(1) Cutaneous sensors. This category covers skin mounted sensors and we include single point devices, imaging array sensors and artificial skins.
(2) Sensing fingers. Tactile sensors are often built into rigid finger structures in order to measure performance and test their capabilities in probing and exploratory tasks.
(3) Soft materials. Recently softer materials have become of interest as potential components for tactile fingers.
(4) Industrial robot grippers. This is one of the original application areas envisaged for tactile sensing. However, we find little significant recent development.
(5) Multifingered hands. Highly actuated artificial hands are necessary for dextrous manipulation tasks. This involves much consideration of integration issues and sheds light on the role of tactile sensors.
(6) Probes and whiskers. Fine probes and whiskers can be used to detect points of contact and discern their spatial positions. Recent work has investigated such active touch sensing devices.
(7) Analysis of sensing devices. The analysis and evaluation of technological developments is a vital part of good science. This category covers material that sheds light on the design, characteristics and performance of sensing devices.
(8) Haptic perception. Active and haptic sensing combines cutaneous sensing with the actions available to an agent such as a robot arm in an integrated and coordinated control regime. This field shows how tactile sensing plays an intimate and complementary role in highly integrated perceptual systems.
(9) Processing sensory data. This category covers methods and algorithms for processing tactile sensory data. It ranges from data interpretation using neural networks, fuzzy logic and model-based approaches, to sensor data fusion where tactile data must be integrated with sensory data from other modalities.
(10) New application areas. Active areas identified in this survey are medical and service industries, agriculture and food.

A selection of the material we surveyed is reported below under these interest areas. We have cited papers which either make a significantly novel contribution or which typify papers reporting on a particular tactile sensing issue.

6.1. Cutaneous sensors

The production of new designs and configurations of sensors continues apace. However, most of the possible forms of physical transduction methods have now been explored and there seems little scope for new fundamental transducers, see Nicholls [3] and Russell [5] for details of the basic transduction methods. The current research offerings are mainly concerned with novel packagings, better designs, improved engineering and more complete analysis.

There is an important distinction in tactile sensing between extrinsic and intrinsic sensing. Extrinsic sensors are devices that are mounted at or near the contact interface and deal with localised regions, while intrinsic sensing refers to the derivation of contact data from force sensing within the mechanical structure of the system. Force sensing produces information such as contact vectors and point locations. See Ciccetti et al. [6] for an example of an intrinsic sensor: this is a miniaturised six axis force sensor built inside a finger. This survey is focused on extrinsic tactile sensing, and so we do not cover the details of such intrinsic designs (which are usually based on strain gauges) or any other forms of force/torque sensors.

A wide range of tactile sensors are reported on in the literature. When designing or assessing a sensor, the following points should be considered for selecting design criteria:

- Parameter(s) to be measured—what parameter will the sensor measure (e.g., force, torque, presence/absence of contact, thermal conductivity, slip, etc)? What is the range of detectable measurements?
- Spatial resolution—what are the dimensions of the sensing area, and what is the spatial distribution of the tactile elements ('tactels')?
- Response profile—what is the sensor's response to increasing/decreasing stimuli (this should be a monotonic response that is stable, repeatable and without hysteresis)?
- Time resolution of the sensor—how many samples per second?

6.1.1. Sensing devices

There are two main forms of extrinsic tactile sensor: single value sensors and arrays of integral sensing elements. In both cases integrated circuit technology has been used to fabricate chip based devices. We illustrate these ideas below with selected work from the literature.

Beebe et al. [7] describe a silicon based piezoresistive force sensor that addresses the problems of robust packaging, small size and overload tolerance. The sensor measures the force (rather than pressure) applied to a 4 mm raised dome on the device surface. The device exhibits a linear response, good repeatability and low hysteresis, and has a flexible and durable packaging. Arrays could be fabricated with an estimated spatial resolution of 2–4 mm. Trials are described using the device as a finger mounted sensor for measuring pinch force.

Wolffenbuttel et al. [8] have researched extensively into silicon fabricated sensors and see this approach as a way of avoiding some of the problems associated with elastic membranes such as hysteresis. Their work on piezoresistive and capacitive micromachined sensors has produced designs for arrays of force sensing elements using diaphragms or cantilevers as the sensing principle.

A combined three-axis force and slip sensor has been described by Yamada and Cutkosky [9]. A domed tactile head transmits force to three nibs that each rest on polyimide resistive sensor pads. The applied force is resolved into three axes and slip is detected by a piece of piezoelectric PVDF film moulded into the head. The signal rates reported were 125 Hz for force sensing and 1 kHz for the stress rate sensor.

Kolesar and Dyson [10] describe a sensor based on an 8×8 array of sensing sites on a CMOS device covered with a PVDF polymer film. Piezoelectric materials are now widely used in tactile sensing, due to their sensitivity and availability in various plastic forms. The Kolesar and Dyson sensor includes MOSFET amplifiers on the chip which covers an area less than 100 mm^2 and is compatible with finger tip applications. It features a pre-charge bias technique which initialises the sensors before each cycle in order to reduce the problems of stability and reproducibility that have long been associated with piezoelectric effect devices.

Gray and Fearing [11] report on an 8×8 capacitive fabricated array that is 1 mm^2 in area. This gives a spatial resolution at least 10 times better than the human limit of 1 mm and is intended for medical applications involving small manipulators and endoscopic surgery. It could be mass produced and therefore disposable—a fairly novel idea in tactile sensing. Severe hysteresis was the main drawback.

Omata and Terunuma [12] point out that most sensors are incapable of sensing many of the range of physical properties that materials exhibit. Most sensors measure pressure or force and are unable to sense many effects that are experienced by humans, e.g., friction, stickiness, texture, hardness, and elasticity. With a view to palpation applications in medical examination, they argue that hardness and softness detection require different approaches, especially for sensing variations in soft tissue, and describe a sensor that approximates to humans in this respect. The sensor has a piezoelectric resonator, driven at 61 kHz, and works on the principle that contact with an object will cause a change in resonating frequency. The device is packaged into an acrylic tube, 15 mm diameter by 65 mm long, and in simulated cancer tests it detected 3 mm diameter glass balls 20 mm below the surface of a silicone breast model. The main problems were the need to maintain a constant contact pressure (20 grams) and a slow time response.

Mixed function sensing is an interesting possibility. Li and Shida [13] describe a multifunction sensor consisting of two interleaved planar spiral coils 35 mm in diameter. The coils can be used in three ways: as a capacitive sensor where the dielectric constant of the object affects the capacitance between the coils; as an inductor where the frequency transfer function between the coils can distinguish a magnetic, non-magnetic or nonconducting material; and as a thermal sensor where one coil acts as a heater and the other a temperature sensing resistor. Problems include the thermal time response of several seconds, the need to insulate metallic objects (cellophane tape was used), and an implicit assumption of constant applied contact pressure.

Monkman and Taylor [14] also report on a thermal sensor; in this case based on a pyrometer design that gives an order of magnitude improvement in response time over other thermal methods. As thermal sensors are fundamentally limited owing to their sensing of a single material parameter, Monkman and Taylor also argue for multifunction devices and describe a combined thermal, electrical and mechanical sensor.

Another, and perhaps neglected, aspect of tactile sensing concerns extensive surface sensing over a bounding envelope or skin. There are obvious applications for a sensing skin that can cover robots or other moving equipment in order to detect contact with objects or humans in a local environment. An experiment with a full-body sensing suit for a small robot is described by Inaba et al. [15]. The company Tekscan [16] produces a range of sensing systems including pressure mats, in-shoe foot pressure arrays, and other gait and stance measuring systems. The sensing principle is based on arrays of resistive elements embedded in a large area flexible film only 0.18 mm thick. The F-Scan system allows the flexible sheet to be cut to shape and inserted into shoes for real-time pressure measurements. This application has 960 sensing tactels each covering around 5 mm^2. See Donaghue and Veves [17] for a review of such systems, including optical pedobarographs that use the same optical internal reflection principle as used in some tactile sensors. Clearly, if fitted to a robot's surface area, this sensing film could be an ideal skin for service robots that work in cooperation with humans and must detect any collisions or contacts. Work by Yamada et al. [18] has dealt with the related problem of protecting the joints and elbows of robot manipulators. In this case a fixed skin is unsuitable as moving joints have constantly changing surface envelopes. Yamada used helical springs with 48 tactile sections; contact on a section causes an LC circuit to be activated and by swept frequency scanning all sensors can be read through a single pair of wires.

Another notable commercial development is the FSR (Force Sensing Resistor). These are resistive polymer film elements manufactured by Interlink [19] and are widely used in pointing and position sensing devices such as joysticks. FSRs, being inexpensive and readily available, are found in many experimental tactile systems.

A different but promising looking technique is acoustic ultrasonic sensing. Microphones are known to be useful for detecting surface noise that occurs at the onset of motion and during slip. Ando and Shinoda [20] describe a device that senses contact events from their ultrasonic emission at the contact point. A PVDF polymer is used in a 2×2 array of receivers to localise the contact point on a silicone rubber sensing dome. They reported that this sensor is very effective in detecting slip and surface roughness during movement.

In a variation of the design, Shinoda and Ando [21], used ultrasonic transmitters and receivers to detect changes in wavefronts due to distortion and could detect displacements as small as ten micrometers. Hutchings, Grahn and Petersen [22] also describe an ultrasonic sensor but this time using a cross field transmission in which the compression of an elastomer pad changes the transmission properties. Another sensor by Shinoda and colleagues [23] uses microphones to detect changes in air pressure within cavities inside a raised spherical silicone dome. A novel method of discriminating surface composition was used by a mobile robot that tapped a boom-mounted microphone on the floor like a blind person's cane [24]. The acoustic signatures from the impact allowed six floor types to be classified with an accuracy of 98%.

6.1.2. The tactile inversion problem

Many array sensors employ a protective covering made from an elastic material. This gives mechanical compliance, which assists the grasping process and increases the robustness of the device. However, this configuration raises a serious difficulty, known as the inverse tactile transduction problem. If an object is pressed into the surface of an elastic layer then, from analysis of the bulk material properties and the surface shape, we can calculate the stresses that will be generated down at the sensing points—this is forward analysis. In inverse analysis we wish to compute the changes on the surface from the sensed data gathered remotely through the elastic medium. Unfortunately, this does not give rise to a unique solution as there is no one-to-one correspondence between the stresses deep within an elastic material and those that are applied normal to the surface. In other words, a given pattern of sensory values may be caused by many different patterns on the surface. This is known as an ill-posed problem and can not be solved by direct analysis. This particularly applies to fine form discrimination and it can be seen that elastic materials act as a low pass filter, only transmitting large scale spatial patterns and attenuating any fine detail.

A useful illustration of the inversion problem and its ill-posed nature is given in Nowlin [25].

The tactile inversion problem has often been tackled by using a shaped membrane featuring ribs, tabs or other forms of raised surface nodules. Yeung et al. [26] describe the use of this technique in enhancing the sharpness and resolution of tactile images as compared with uniform membrane surfaces. They use a 16×16 sensing array, employing FSR resistive components. By keeping the nodules in the compliant overlay entirely separate, the compression of a nodule is made independent of the state of other nodules and local crosstalk is reduced. Another design using an elastic skin with raised tabs, containing a force array and a dynamic sensor, is described by Jockusch, Walter and Ritter [27].

An optical technique based on the birefringent generation of a phase-lead in circularly polarised light in a photoelastic layer is proposed by Saad et al. [28]. This relies on the linear relationship between applied force and phase-lead and uses an optimisation function to address the inverse tactile problem. The method needs further testing and its computational complexity may prove to be a problem.

Another proposal involves an array of tensor cells sparsely embedded inside the volume of the compliant sensing cover [29]. This aims to resolve all six axis stress components in the sensing membrane and thus provide a different solution to the problem of tactile inversion. However, the results from a later design using ultrasonic resonant cavities [30] suggest that the particular stress tensor used may give ambiguous output cases.

Many papers on array sensors with compliant membranes now recognise the tactile inversion problem and include some analysis or treatment. Section 6.7. gives further detail on this topic.

6.2. Sensing fingers

One way of investigating the performance of tactile sensors is to construct an artificial sensate finger than can be used to probe and explore the local environment. Researchers have usually designed such fingers as cylindrical devices with the emphasis on sensing on the hemispherical tip or over a curved surface region near the tip. Dario [31] gives an example of a three-sensor finger being used to probe and identify unknown materials.

Problems with a stiff piezoresistive sensor for measuring grasped surface profiles were overcome by Russell and Parkinson [32] who built a soft, water-filled finger covered in a neoprene skin. Sensing was achieved by resistive measurement of the volume of liquid between the intersections of an 8×10 grid of row and column wires. Another design using a stiff core, but with a sponge body and rubber covering over FSR sensors was described by Borovac et al. [33]. In a two fingered experiment the extra compliance assisted self accommodation during a successful peg-in-hole assembly task while any sensed errors were compensated by the control system.

In a comprehensive paper Howe and Cutkosky [34] examine the problem of detecting fine surface features and textures. They use a stress rate sensor for intermediate frequencies.

Studies of human finger properties [35] have shown a wide range of friction coefficients. Unlike rigid robot fingers these coefficients decrease with increasing normal force. Also friction during backwards movement of the finger is larger than for forward movement, probably due to stiffness caused by the nail.

Shimojo and Ishikawa [36] show how surface roughness can be measured by sliding a pressure sensing array over a surface and analysing the spatial frequency using variable filtering techniques.

A general consensus is now discernible in that a general purpose sensing finger will require at least two types of tactile sensor—one for contact point localisation and fine form spatial discrimination, and one for detecting more spatially diffuse dynamic events such as contact slip. This is in accord with our knowledge of human tactile receptors, where at least four different types of receptor are tuned for different spatial and temporal resolutions [37]. There seems to be an inverse relationship between these i.e. the better the frequency response of a receptor the worse its spatial resolution is likely to be, and vice versa. We see (in section 6.8.) that work on haptic perception shows that intrinsic force sensing is another complementary component of an effective tactile system. Hence intrinsic force and torque sensing is also likely to be included for kinaesthetic sensing of grasp or contact configuration data.

See the fingers of Taddeucci [38], Howe [34] and Dario [39] for examples of such combined designs. These papers also give the current state of the art.

6.3. Soft materials for tactile sensing

In the past, most devices have relied on fairly rigid, solid materials for their construction, including the all important contact surface. Perhaps this was the natural place to start as rigid systems have less complexity and there are less variables to control. Following studies of human tactile performance and the physical nature of the tissues and skin, it now seems that softer materials may have much to offer. Elastic overlays and compliant contact surfaces are often advocated for their frictional and other properties, although their low pass filtering behaviour can be a disadvantage. But now even less rigid materials, such as fluids and powders, are being examined.

Shimoga and Goldenberg [40] have examined a range of materials with different consistencies and found that soft surfaces have more desirable characteristics for contact surfaces than hard materials and that, of the soft materials, gels are better than plastics, rubber, sponge, or paste, with powders being the second best. The factors considered included impact and strain energy dissipation, conformability to surfaces and hysteresis effects.

Sawahata, Gong and Osada [41] have described an interesting piezoelectric effect in polymer gels. A weak polyelectrolyte gel was shown to change pH when mechanically compressed. The reverse effect also occurs—an applied potential causes the gel to swell visibly. Using polyacrylamide, the authors constructed a simple tactile cell which captured the electrical change and demonstrated a few millivolts being generated on loading. The fact that human tissue is also composed of electrolytic materials with very similar mechanical properties suggests intriguing possibilities for new designs of sensing fingers.

A different use of gels involves electrorheological effects, for example the application of a strong electric field across a suitable gel can change it from a fluid to a plastic solid. Voyles, Fedder and Khosla [42] have designed a tactile actuator on this principle together with a matching sensor. The actuator/sensor pair have male/female symmetry for the purpose of remote monitoring of touch sensing. The fingertip-shaped sensor detects contact events on its external surface using a gel layer as a dielectric in capacitive sensing, while the similarly shaped actuator (or tactor) recreates the remotely sensed tactile events on its internal surface by changing the solidity of areas of the gel in contact with the human operator. Taylor et al. [43] present experiments on a 5×5 tactor array using a rheological fluid (silicone oil with 24% volume of particulate content). Such devices appear useful for tactile feedback applications but a serious drawback is the high voltages required (e.g., 2 kV).

6.4. Industrial robotics and grippers

The emphasis on applications in tactile sensing has shifted away from the industrial arena. Very few industrial or commercial devices are available and even less are in regular application in industry.

This category was intended for tactile sensing in robotic devices that had very strong external engineering requirements. For example, parallel action grippers, powered assembly tools and industrial machines of all kinds were included, but dextrous robot hands were not. Several papers were found but these are not presented as they were very specialised. Of course, there is a large literature on industrial robotics, e.g., grasping mechanics and kinematics, but it contains little tactile material.

The criteria for sensors to be acceptable in robotic applications have been listed as robustness, reliability, accuracy and high resolution. It seems likely that some applications would have tolerated lower levels of accuracy and resolution, and so we conclude that the more important requirements of robustness and reliability could not be satisfied or demonstrated at suitable levels and at the right economic price for industrial acceptance.

It may be surprising to find so little work on tactile sensing in industrial robotics and automation—considering this had been promoted as a major future application area. The reason for the shift away from the industrial arena, and towards other more unstructured domains, may be more to do with the strength of application pull and the failure of technology push. Many papers have justified their designs and results by referring to various suggested criteria and specifications for desirable devices, e.g., that of Harmon [4]. However, although widely quoted, these specifications were essentially speculative. They only have meaning if the task to be automated is best done with the technology proposed in the way envisaged. It is important to assess the requirements specification of any sensing task in general terms without promoting any particular technology. Thus industrial tasks with apparent tactile sensing needs may turn out to be better served by other methods. Technical superiority is only one dimension; managers might decide that vision or 'spatial switches' provide solutions that are better in terms of cost, minimising disruption, reconfiguration, retraining, etc.

6.5. Multifingered hands for dextrous manipulation

Robotics has always had a strong interest in the design of artificial hands but these are complex and expensive to develop. Consequently only a few different designs have been reported [44], most consisting of three of more multi-jointed fingers in an arrangement similar to the human hand. Despite the control challenge posed by the many degrees of freedom in a fully actuated version, the appeal of anthropomorphic designs is in the promise of reproducing manipulation dexterity approaching that of humans.

Tactile sensors have been less prominent until recently in this area but Johnston et al. [45] report on a comprehensive suite of sensors designed to fit all the finger segments and palm of an established multifingered robot hand. The sensing method is capacitive and there are 13 separate pads, containing arrays on 2.77 mm centres, giving a total of 744 sensing sites. The scanning rate is 17 k tactels per s, and the authors claim that the low sensor mass and high damping ratio allow the system to be used in transient force control. This system is notable as a commercially available product.

A strong advocate of multifingered robot grippers for dexterous manipulation is the group of Howe and his co-workers. Howe [46] argues that effective, high performance dexterous manipulation must involve fast real-time processing of information relevant to the different phases of grasping tasks as situations change from position to force control, from rolling to slipping or sliding, and power grasping.

Unfortunately, we do not yet know enough about the most suitable or even necessary information for any given manipulation task. For example, to detect contact we may have available a range of different sensing techniques all with different characteristics but selecting between these for a given task is a difficult problem. Howe stresses that static arrays have limited applicability and that the essential aspect for manipulating objects in real-time is smooth and accurate fine control.

The need for real-time control and dynamic sensing for rapid detection of contact events raises various issues, as described by Howe [46]. Some of these issues are dealt with by Son and Howe [47] in which contact events, the contact shape and incipient slip are all handled using a stress rate sensor that can detect transients. This sensor uses piezoelectric polymers and a ribbed structure for localising contact events.

Son and Howe [47] examine the problem of uncertainty in orientation of grasped objects—for an object held between two cylindrical fingertips, the error in poise angle due to friction will typically be around 15°. Using an 8×8 capacitive array, tactile information was used to correct alignment errors in a pig-in-hole insertion task. Son and Howe show how tactile sensing can reduce kinematic errors in stiffness control by locating precise contact points and tracking their changes. However, the method relies on assumptions about the shape of the grasped object.

Another group that have extensively explored multifingered systems is that of Maekawa, Tanie, Komoriya and colleagues. These researchers have exploited the optical transduction method that they and the authors simultaneously discovered in 1984. In [48, 49] they describe the novel innovation of reshaping the internal reflection optical method into a hemispherical design (an optical waveguide). This has the advantage of giving the exact location of a contact point on a fingertip (in polar coordinates) and also, by using a preformed elastic cover, solves the problem of sticking that occurs between the rubber membrane and the optical surface. The experiments report a fast response time of 0.078 s. Such sensing ability allows contact points to be tracked during rolling manipulations, as described in [50, 51]. Tactile feedback is used dynamically to keep the grasp forces within the friction cone thus giving stable real-time grasp control. These results are very similar to those from the Son and Howe experiments. In [52] the data derived from tracking contact during rolling is used to estimate the curvature of the object.

6.6. Probes and whiskers

In the industrial manufacturing arena, touch probes have been developed to a very high degree of sophistication. Coordinate Measuring Machines are extremely accurate systems for recording the profiles and spatial geometry of object surfaces. These expensive systems use sophisticated binary touch sensors combined with high precision spatial actuators and are quite different in purpose and design from the tactile sensing issues addressed in this survey. Nevertheless, the idea of sensing objects by point contact with a touch probe rather than by measuring areas of contact offers alternative possibilities for tactile sensing. Instead of ‘spatial switches’, however, we can use a probe as an active wand thus gaining much more spatial information. Tsujimura and Yabuta [53] have used knowledge of the deflection characteristics of a flexible probe and the force/torque values experienced at its base to compute the position of the contact point. In order to disambiguate false contact cases, Russell [54] added switches to a similar sensor to detect contact at the tip and bending at the root.

Such whisker probes have the potential to be fast, accurate and cheap. They are essentially single point sensors and therefore are local and have low bandwidth, but they may offer interesting possibilities such as being disposable. In a series of papers, Kaneko and colleagues have argued for the utility of active whiskers by analogy with insect antenna and feline whiskers. In the experiments described [55] a fine whisker is moved by a specially designed actuator drive that incorporates torque and position sensing. With a simple sweep action the contact location is estimated from knowledge of the compliance of the whisker and the assumption that all objects to be detected are rigid. For simple bending the contact point is determined by equations with two unknowns and the values of torque and deflection at the root allow these to be solved. Work on dynamic analysis [56] shows the effects of changes in natural frequency after contact and a 3D version [57] exposes the need to deal with lateral slip. In order to remove the assumption of a stiff environment Kaneko et al. [58] have added a vision sensor to discriminate bending in the whisker from compliance in the objects. There seems to be little work in this area as all the Kaneko papers reproduce the related work section from Russell [54].

6.7. Analytical Progress

While the 1980s can be seen as a period of exploration that proposed a wide range of novel sensing methods, more recent work shows a concern for analysis and scientific understanding of the role and process of tactile sensing.

As mentioned above, for unknown objects in unstructured manipulation tasks real-time sensing of contact location is necessary. Son, Cutkosky and Howe [59] have compared the use of tactile arrays and force-torque sensing for locating contact points during gripper/object manipulation tasks. Their experimental study showed that both intrinsic and extrinsic methods could be effective with less than 1 mm error in contact location.

Ellis, Ganeshan and Lederman [60] have taken a rigorous approach towards designing a sensor for a given task and analysed the requirements for sensing the inertial properties of a grasped object. They rejected sensors with compliant surfaces (because they lose too much detailed strain information) and through careful analysis produced a strain gauge based design that is rugged and has high accuracy.

A number of investigators have used finite-element (FE) models for the analysis of material deformation and stress/strain relations in tactile devices, e.g., for a detailed FE analysis of a sphere in contact with a linear elastic plane see [61]. Ohka et al. [62] describe a design based on the optical waveguide principle using large column shaped tabs on a silicon rubber sheet. The tabs can be compressed or displaced along three directions and smaller cones on the underside of the sheet are distorted in a way that reflects the contact forces. A detailed FE mesh model was used to analyse how the materials would deform.

The inverse tactile transduction problem was examined by Ricker and Ellis [63] who used FE analysis as an alternative to the classical solid mechanics approach with linear elastic half-spaces. They showed how different contact shapes can produce similar sub-surface strain profiles and how shear strain can complement the normal strain field. They argue that classical analysis may work for planar sensors but is inappropriate for sensors with finger shaped geometries. Ellis and Qin [64] continue the critique of previous analyses and are ‘not optimistic’ about sensing fine form geometry from strain data within a rubber-like sensor based on traditional solid mechanics methods. The radius of the contact area is the only feature they feel can be detected with confidence.

Nicholson and Fearing [65] have shown that methods for deriving object curvature are sensitive to both calibration techniques and contact models and suggest sensor construction aspects determine the relevance of the analysis and processing method. Another study of the low-pass filtering effect of compliant tactile surfaces, again using FE methods, is described by Shimojo [66]. Results show the reduction in gain with increasing thickness and changes in material properties of an elastic cover. An alternative approach to the inversion problem is to develop a forward model in which changes in tactile images are related to changes in position. Chen, Zhang and Rink [67] have produced a tactile Jacobian that controls a tactile-servo for surface following. The Jacobian has to be constructed piecemeal beforehand and stored in a look-up table.

Slip detection is an important tactile sensing topic that has also been analysed in detail. Holweg et al. [68] describe slip as having four stages: pre-slip tensioning, start, post-slip movement, and stop. They report on a joint investigation into two methods using a rubber-covered 16×16 resistive array. The two methods are complementary, one dealing with the onset of slip and the other detecting movement. Their first method used a FFT to analyse the shifting of the centre of pressure distribution that occurs just before slip starts. The low frequency components give a clear indication of incipient slip. In the second method, a power spectrum density was taken to detect the 65 Hz signal generated during slip by the 'catch and snap' behaviour of the rubber at the contact interface.

Incipient slip signals are detected by humans when localised slipping occurs just before gross sliding at the contact surfaces. To sense this effect, Tremblay and Cutkosky [69] have used skin acceleration sensors embedded in a foam finger. A silicone skin covers the foam and is covered in small protrusions that produce small vibrations when they slip. The system was able to detect incipient slip, compute the friction coefficient and adjust the applied grasp force to compensate.

Son et al. [70] comment that acceleration sensors do not give much spatial localisation and have developed a stress-rate sensor using PVF2 piezoelectric film. This was able to detect local skin curvature and some fine surface detail. They suggest that array sensing is best used for spatial frequencies in the range 0–10 Hz, stress-rate sensors are best for 10–50 Hz and skin acceleration sensors are effective in the range 50 Hz–1 kHz. The importance of incipient slip tactile data for humans has been confirmed by telemanipulation experiments with a master/slave system [71]. Two fingered pinch grasps were performed by human subjects and dynamic adaptation and recovery from slip was clearly demonstrated over a remote link.

6.8. Haptic perception, telepresence and virtual reality

Most early work dealt with static tactile images or contact events. It is useful to remember the different roles of non-static sensing in order to distinguish their requirements and purpose. We define *Active Sensing* as a dynamic form of tactile sensing where relative movement of the sensor is involved. For example, rolling contact can be used to gain shape information or squeezing might be used to estimate elasticity properties. The term *Haptic Perception* refers to the integration of cutaneous surface sensing with kinaesthetic data derived from the position and movement variables of the manipulator system. *Teleoperation* and *telepresence* are concerned with the remote human operation of a handling system and the authentic feedback of a range of sensory modalities. Finally, the idea of *Virtual Reality* (VR) deals with the creation of synthetic sensory experiences for realistic simulation scenarios.

Active sensing is now well represented in the literature and is featured in many of the papers discussed in this survey. Haptic Perception emerged in the 1990s and is now accepted as a major approach in tactile sensing work. Teleoperation and telepresence systems must directly confront the problems of sensing, encoding and reproducing tactile sensations and so will be of interest here. VR does not involve any remote actuation or sensing other than the delivery of relevant stimuli to the participant. However, some of the features of VR technology are closely related to telepresence and we will include some relevant work.

Examples of active sensing schemes are seen in studies of tactile tracking, where a robot must trace out the shape of an unknown surface, ideally in real-time, by maintaining contact between the surface and a tactile sensor. Chen, Rink and Zhang [72] provide a mathematical surface notation that links contact constraints and kinematics, and then derive a tactile driven control scheme that performs surface tracking. Another approach to curvature tracking is to use one or more fingers of a multifingered hand; Charlebois et al. [73] use surface normals from surface tracing experiments to recognise object shape using the idea of Lederman's Exploratory Procedures. Others who have experimented with tactile procedures include Buttazzo, Bicchi and Dario [74], who used three separate routines to deduce hardness, texture density and friction coefficients.

Haptic Perception is concerned with relating and reconciling local tactile information to the global spatial structure of the objects in the sensed environment. This means that tactile data is necessarily sparse and has to be integrated via some form of kinaesthetic spatial framework. Caselli et al. [75] explore the use of two kinds of polyhedral volumetric shells for building up models of unknown objects during exploratory action. This work assumes that the objects are convex and are larger than the sensor contact areas. An example of the converse case where the object surfaces are smaller than the sensor surfaces is seen in Kinoshita [76], where a lattice of object features in terms of points, edges and planes can be constructed. In both cases the spatial structure of the objects provide the linkage between different local tactile data; a linkage that can be seen as characteristic of the encountered objects or as a map of kinaesthetic exploration. (We notice that concave surfaces can be explored using tactile probes [77].) Beccari et al. [78] continue to explore sparse tactile data and show how the pose of objects can be recovered using principal axes analysis with 35 contacts being sufficient for pose-independent recognition of any one of 20 objects. They also discuss the differences between tactile and visual data and argue that feature based methods are not appropriate. For further background on the haptic aspects of tactile sensing see [3], and for the current state of the art of haptic exploration with dextrous robot hands see [79].

A telepresence system is normally arranged to transmit some desired operator forces and movements to a slave system which will then reflect back to the operator the reactions and sensed events. This means that both tactile sensing and display are required and, ideally, the system mechanisms must be structurally transparent, i.e., the only forces and sensory data experienced by the operator should be those generated solely from the application and not from the system itself.

Kontarinis et al. [80] report on an experiment with identical two-fingered master and slave manipulators fitted with force and tactile feedback. The tactile system used the Fearing design [81] of an 8×8 capacitive sensing array on 2 mm spacing and a tactile display consisting of an array (6×4) of pin actuators (shape memory alloy) arranged under the operators fingertip. In a simulated medical trial subjects were asked to locate a hard rubber cylinder inside a block of foam rubber. The error was not more than 1 mm for 50% of the trials but without tactile feedback the mean error was over 13 mm. These results confirm the conjecture that force reflection alone is not sufficient for fine form sensing.

Another experiment, Cohn, Lam and Fearing [82] used a tactile sensor array and display device to evaluate the transmission of tactile force, pattern and displacement. Displacements as low as 0.1 mm were detected by human subjects. Fearing, Moy and Tan [83] discuss the problems of spatial detail and aliasing in tactile displays and show why an elastic (low pass) layer is necessary between human finger and the tactors. A novel finger tracking device is described by Yoshikawa and Nagura [84] in which contact is correlated with events in a virtual environment. As the user touches virtual objects so the tracker makes contact and applies resistance.

Caldwell et al. [85] describe experiments with a multi-sensor glove for feedback of a range of tactile signals. Taking inspiration from the human sensory nervous system they designed a glove that could generate sensations of contact force, fine form surface detail and thermal conduction. The actuators used were piezoelectric pulse generator (high frequencies for textures), piezoelectric bi-morph (medium frequencies for edges), air bladders (low frequencies for contact forces), and Peltier effect heat pump for thermal effects. Shimojo et al. [86] also use a glove with a comprehensive set of pads that sense the loading on finger sections and palm using conductive rubber methods. The experiments used a range of instruments to measure grasping posture, wrist position, applied forces and to capture video images during task performance.

An interesting way of controlling the sensed roughness of a surface is described by Watanabe and Fukui [87]. The application of ultrasonic vibration to a solid surface reduces the perception of high frequency spatial features, thus subjects reported a rough rusty surface as ‘smooth’ when vibrating at 75 kHz. The effect begins at about 10 kHz and saturates at around 20 kHz. Conversely, an increase in perceived roughness was reported by subjects when short bursts of vibration (duration 10 ms) were applied. The amplitude modulation of the burst seems to determine the perceived surface structure and even ‘virtual protrusions’ were reported. The mechanism responsible may be simulating the ‘catch and snap’ phenomenon of sliding friction with elastic surfaces. The idea of a controllable friction/texture surface seems to offer exciting possibilities for tactile feedback.

Many authors in the field of tactile sensing for Haptic Perception, Telepresence and Virtual Reality refer to the psychophysical and physiological literature to gain insight, understanding and support for new developments. For example, visual information may need to be coordinated with haptic information in order to resolve redundant or complimentary data. In this case, results suggest that vision is usually the dominant sense when conflicts arise.

Wu and colleagues [88] have studied human perception of length and curvature of objects using vision and tactile sensing. The results showed how humans overestimate and underestimate parameters during sensory fusion situations and suggest how these might benefit the design of virtual sensing systems.

Another consideration is the role of dynamic contact sensing, that is, the detection of grasped object properties such as size, mass and moments of inertia by sensing their dynamic influence on the system. With so much still unknown, much theorising and debate is raised in this area but nevertheless valuable ideas are gained by studying the human tactile system. An example is seen in the discussions about the perception of the length of a statically grasped rod; Lederman, Ganeshan and Ellis [89] argue in detail that teleoperation systems (handling long objects such as rods) will need to modify the force and torque feedback to take account of human bias in weight and length perception. This work also derived the design of a tactile sensor specifically for dynamic sensing, described in [60].

6.9. Tactile data processing

As any sensing technology matures, we should expect a section of the literature to focus on the processing of the data generated. This involves not just signal processing but interpretation and correlation of the signals in terms of the semantics of the application. As we have seen, areas where considerable processing could be required include the tactile inversion problem and the extraction of shape and curvature. The techniques that are currently popular for such tasks in similar fields are: neural networks, fuzzy logic methods, rule-based systems and model-based systems. These can all be found in the tactile sensing literature.

A fuzzy logic method for discriminating material types from tactile data is described in Li and Shida [90]. Tactile sensors of four types (thermal, inductive, capacitive, optical reflectance) were used to collect data on seven different materials (wood, rubber, styrene and four metals). Although high discrimination rates were achieved this work is at an early stage and the results were not conclusive.

Other fuzzy logic methods have been tried, as well as a few rule-based systems, but the most popular processing technique appears to be neural networks. Part of the attraction is the speed of parallel nets that will be valuable for real-time sensing. Neural processing methods have been reported for learning parameters for unknown surface shapes [91] and for detecting discontinuities and other defects in oriented textured surfaces [92]. Pati et al. [93] describe an approach to the tactile inversion problem which uses an analogue neural network for deconvolution. Further development, to consider stress tensors rather than just normal forces, is given by Caiti, Canepa and De Rossi [94] who use regularization theory and experiments with two types of network (back-propagation and radial basis functions). Another way of dealing with the tactile inversion problem is to incorporate additional information. Motor actions were used by Rucci and Dario [95] in a neural network to correlate tactile changes with small motor movements while maintaining tactile contact. In a further development Rucci and Bajcsy [96] show how visual data can be coordinated with tactile data as a step towards a general framework for integrating multimodal attention stimuli.

A major concern in sensor data processing is the problem of merging or fusing data from more than one sensor or even from sensors of markedly different characteristics.

This is difficult because the data from physical sensors are rarely easy to reconcile, and noise and distortion must be separated from genuine differences in sensed variables.

Yamada, Ishiguro and Uchikawa [97] use a model-based method for fusing sensor data from vision and tactile sources but the tactile data is treated as a second stage refinement of a coarse parametric model.

Joshi and Sanderson [98] contrast *homogeneous* sensor data, where all data comes from the same type of sensor and the fusion can take place at the *signal* level, and *heterogeneous* sensor data, where different sensing modalities may be employed and then fusion must take place at the *feature* level. Extending their earlier work on single sensor model matching [99], Joshi and Sanderson have produced a general model-based fusion method based on information-theoretic criteria. A worked example on fusing tactile and visual data is given.

This approach automatically weighs the priority of sensor data in terms of sensor accuracy, precision and resolution and has good rejection of outliers and appears to be general and very robust. See [100] for improvements and further analysis.

6.10. New application areas

During the 1980s, most authors predicted that the major application area for tactile sensing would be industrial automation tasks such as robotic assembly. Several commercial tactile devices were marketed, clearly targeted at this area. However, the demand for such sensors proved to be low, as did the numbers sold. Commercial force sensing robot wrists are still much more numerous that tactile systems. There are still very few fully developed applications of tactile sensing but this section considers current trends and estimates the potential role of this technology in the future.

We see three main fields where tactile sensing is likely to play a key role. These are: medical procedures, especially surgery; rehabilitation and service robotics; and agriculture and food processing. We consider these in turn.

6.10.1. Surgical applications

Surgery is perhaps the most exciting and rapidly developing area where tactile sensing is actually of central importance. Minimally Invasive Surgery (MIS) is only 10 years old and yet is now routinely used as the preferred choice for many operations. However, despite its advantages, MIS severely reduces the surgeon's sensory perception during manipulation. Surgery is essentially a visual and tactile experience and any limitations on the surgeon's sensory abilities are most undesirable.

For example, in laparoscopy long slender tools are inserted through small puncture openings in the abdominal wall and the surgeon uses a range of tip mounted instruments guided by video feedback images. As the instruments are rigid rods and effectively have fixed pivots at the entry points, the available degrees of freedom are restricted and therefore demand extra operator expertise. Voges [101] reports the main difficulties experienced are: restricted manipulation mobility, lack of depth from 2D vision and the almost complete lack of a sense of touch. The relevance of telepresence is clear and Voges predicts that future systems will have new designs of flexible instruments with greater mobility, force reflection, 3D monitoring and data enhancement. A table of contrasting features for current and future laparoscopic systems is also given. It is clear that tactile sensing is greatly needed in this area and researchers are responding to the opportunity.

The reason that tactile sensing is so important in surgery is that soft tissue can only be properly examined and identified by assessing its softness, viscosity and elasticity properties. The palpation of tissues and organs is an essential procedure that surgeons value highly. Indeed, surgeons have been known to insert their fingers through the access openings during MIS simply to perform direct tactile exploration [82]. Dario's short but far-sighted review [39] cites medical applications in which the hardness of soft tissues is detected through palpation. Howe et al. [102] discuss the topic of remote palpation technology.

Bicchi et al. [103] gives a good description of the issues in MIS and describes an experiment with a commercial instrument modified to sense force (by strain gauge) and position (by LED and optical detector). By correlating force against deformation the system was able to identify five objects of different elastic properties.

An experiment with a sensor for laparoscopic attachment has been described by Fischer et al. [104]. A 64 point sensor of area 1 cm^2 was connected to a fingertip vibrotaction display.

The medical sensor described in section 6.1. has been used in sixteen cases to localise pulmonary modules [105] and for measuring heart wall stiffness [106]. The ultrasonic tactile method is entirely non-destructive in its use as a sensor and therefore is much safer than other methods using needles. A force sensing catheter tip with a diameter of only 1.6 mm has been built, using an IC pressure sensor, by Tanimoto et al. [107]. The sensor can be used inside blood vessels and allows the surgeon to distinguish frictional resistance from direct pressure on vessel walls at junctions and bends. A microrobot designed for colonoscopy and using a pneumatic 'inchworm' propulsion method is described by Dario et al. [108].

The difficulties of adopting fully autonomous robotic systems in surgery are discussed by Ho et al. [109] and an approach is developed where the surgeon maintains supervision and control but is constrained from driving the cutting tools outside force limited regions.

A series of designs for endoscopic and laparoscopic tools are discussed by Cohn et al. [110] who intend incorporating their tactile telepresence apparatus [82]. An interesting idea raised here is the possibility of using the capacitive tactile sensor, not to measure applied force, but to detect the varying dielectric permittivity of different tissue. Cohn et al. suggest that water, fat, blood vessels, and cancerous tissue might all be discriminated by this means.

An interesting sensor has been developed for orthodontics. Umemori et al. [111] state that it proves very difficult to measure pressure distributions between the lips and cite over 20 measuring devices that have been assessed but have proved unsuitable. In order to assess changes after surgery, they developed a sensor, based on the optical waveguide principle, that can measure lip sealing forces, contact areas and pressure distributions. A striking feature of the design is that it uses disposable cartridges: by selecting inexpensive materials (OHP film, silicone rubber sheet, photographic film) the sensing head could be replaced for each patient.

Such attention to packaging could well be very significant for the success of medical sensors.

6.10.2. Rehabilitation and service robotics

A major concern for the next century is the enormous numerical increase in the elderly population that will generate great economic pressures, especially in the developed countries. This demographic change is well accepted and many governments have initiated programmes of research in health care, hospital services and social support. It is clear that there will be greatly increased demand on these services and researchers are looking for methods of support and assistance that do not involve central services but can be distributed as aids within the home and community. Robotics can play a major role here, but much of what we have learned may not be readily applicable. This is the opposite end of the robotics spectrum from the industrial arena and is concerned with very unstructured and irregular environments and focuses on the major issues of human compatibility, safety and reliability. Interestingly, issues such as accuracy and high resolution are of much less importance.

Dario et al. [112] discuss these issues and describe three current investigations into automated aids for the disabled in hospital and the home involving manipulators and mobility systems. In order to be accepted and operated by the elderly or infirm such aids must extend the very limits of user friendliness; as Dario states [113], interactions with the systems must be assessed in terms such as ‘satisfaction and pleasure’ and ‘the user’s feelings toward the system [must be] kept in great consideration’. An example task for a home service robot is: take a dish of food from a refrigerator to a microwave cooker and, after heating, serve to bed-ridden user [113]. Another human-factors aspect is the physical appearance; it may be necessary for the system to have some anthropomorphic characteristics in order to gain acceptance.

Despite the contrast with industrial robotics, there are some emerging interests in human-robot cooperation within manufacturing. As the next stage in automation, Toyota envisage workers and robot machines coexisting in a ‘safe partner’ relationship. Tobita et al. [114] stresses the need to make automation more attractive to people and describes ways of dealing with the safety issue. The conventions and standards on robot safety state firmly that all active robots must be isolated from human contact. However, if this restraint is to be lifted there are two ways of providing safety: either very comprehensive collision avoidance and fail-safe features must be built in, or the equipment could be designed to be intrinsically safe. Tobita et al. take the latter approach and design low power, reduced weight devices with many safety features. This is rather like producing smarter and more useful power tools for human workers. The other approach is seen in Suita et al. [115] who assume that collisions might occur and design the robot systems with compliant coverings and collision detection and avoidance mechanisms so that any contact will be well below the thresholds of human pain or damage. Ikeura and Inooka [116] show the advantages of variable impedance (damping) control schemes for robots that follow human trajectories in cooperative lifting tasks.

As yet there is little in this area that is new specifically concerning tactile sensing. However, as for medicine, we can see many opportunities where a sense of touch will be a real need. An example is seen in the robot floor cleaner of Ulrich, Mondada and Nicoud [117] which needs to sense the shapes of furniture and other objects in order to clean round them. This is a very new field and is likely to show significant growth in the near future—already new journals, such as *Service Robot* [118] are beginning to emerge. Funding from major sources include the TIDE (Technology Initiative for Disabled and Elderly people) programme of the European Commission and the Real World Computing Programme in Japan. The RWC programme is aimed at developing flexible human assistants that have intuitive abilities, i.e., 'Interactive computers using speech, facial expression, and gesture; systems that infer user's intentions, and robots that can work with humans by learning by example' [119]. For a view of health care robotics in the U.S.A., see [120].

6.10.3. *Agriculture and food processing*

The field of agriculture and food production is now well automated but, like service robotics, also does not feature many new technological advances in tactile sensing. Uses of tactile sensing are often mundane (e.g., binary switches are sufficient and satisfactory to sense crop height in an automated gain harvester [121]), but the importance of this area is its potential for imminent development. Unlike manufacturing automation, the processing of natural produce usually involves high numbers of human operators. This is because the problems of handling soft, delicate and highly variable items by machine have not yet been solved at low enough costs. Various methods for inspection have been developed but the handling and assembly of food produce remains as one of the last bottlenecks to remain largely un-automated in the highly organised food and agriculture industries. Recently, there has been increased interest in the prospect of reducing human involvement in order to reduce hygiene risks, eliminate human errors and use efficient but more hazardous environments (e.g., low temperature factories).

Examples in this field are very specific as a few cases illustrate. Stone and Brett [122] describe a design of intrinsic sensor for monitoring gripping forces and slip during the handling of dough-like materials. Dough gives an example of the requirements for gripping soft, compact objects and relates to soft fruit and confectionary items. Asparagus is another delicate product and a pneumatic gripper with fine force feedback and a fuzzy controller is described by Mattiazzo et al. [123]. Among many other studies of robot grippers for soft objects are the investigations of Naghdy and Esmaili [124] in Australia and Friedrich in New Zealand.

For example, Friedrich and Lim [125] combine research into novel sensory grippers and control modules. The intended application areas are the handling of soft, natural products such as those commonly found in the food industry. They have developed a gripper with hardness evaluation as an integral part of the gripping process and a variety of gripping strategies including active control of slip during object handling.

Despite a long history of gripper design it seems that the time is now right for the integration of our knowledge of force, tactile and spatial sensing with actuation, material design and sophisticated control, to produce some smart soft-product handling systems with abilities comparable with human operators.

7. Conclusions

A number of observations can now be made:

- In tactile device design, a shift of interest is discernible away from novel transduction technology and towards the engineering of sensors. Thus, there are now more configurations that give better reliability, robustness, durability and overload tolerance. Packaging is important with considerations of flexibility, size and disposability all in evidence.
- The previously wide range of transduction methods seems to have settled down with the predominant choices being piezoelectric methods for many devices, with arrays using resistive or capacitive sensing. Strain gauges are still the preferred choice for force sensing. Spatial resolutions have increased considerably and many fabricated IC devices have been designed. New advances have also been made in sensing fine form texture and properties such as softness of materials.
- In our classification scheme, the areas which had grown the most in terms of numbers of publications were: analysis and evaluation, methods of processing tactile data, and medical applications. Little new work was found on tactile sensing in industrial robotics and automation.
- On the analysis side, much attention has been directed at the inversion problem and the dynamics of slip. Also, in manipulation we see much progress: ‘the state of the art in tactile sensing and dextrous manipulation planning control are reaching the point at which autonomous haptic exploration becomes feasible’ (Okamura, Turner & Cutkosky [79]).
- The field is maturing and we see a deeper understanding of human tactile sensing, the physical properties of skin and the recognition that several types of sensor must be involved. Whilst not promoting an anthropomorphic approach, the improved understanding of human systems enables a more integrated approach to be adopted for tactile sensing in mechatronic systems. In an artificial manipulation system, we would now expect to find at least three kinds of sensing being performed: intrinsic sensing of internal forces and torques; shape and contact location sensing using arrays; and dynamic sensors for slip and transient event sensing.

In summary, this survey has found increased emphasis and understanding of device materials, tactile sensing processes and requirements; the recognition of the value of results from dextrous manipulation and telepresence systems; and an emerging engineering approach to sensor packaging. All these, together with the application pull from medicine and service industries, bode very well for the next stage in the development of this fascinating field.

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