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Tactile Sensing: New Directions, New Challenges

Abstract

Over the past three decades, tactile sensing has developed into a sophisticated technology. There has been a longstanding and widely held expectation that tactile sensors would have a major impact on industrial robotics and automation. However, this promise has not been realized, and few, if any, tactile sensors can be found in factory-based applications. Has this technology failed to deliver its expected benefits to robotics applications, or have other factors influenced the development of the field? In this paper, I report on the state of the art and show that tactile sensing has undergone a major change of direction. I revisit the original predictions and expectations, examine the implications of recent reviews, and show how the field has altered course. From current activities and recent trends, I determine the nature of new application areas and pressing developments that hold much promise for the future. There is evidence that tactile sensing will soon play a major role in unstructured environments, particularly in areas such as medicine and surgery, health-care and service robotics, and automated natural product handling.

KEY WORDS—tactile sensing, review of field, new developments

1. Introduction

Sensing technology research seems to progress through a series of stages: first come the ideas and experiments with physical transduction methods, which lead to the invention of new device designs; then laboratory prototypes are built and evaluated, usually involving much analysis; next follow application trials, comparisons, and assessments; and finally, after much reengineering, commercial products are launched. This idealized scenario can be perceived, with qualifications, in the history of computer vision research. A level of maturity has now been reached in computer vision whereby commercial hardware and software packages are widely available and routinely used in industrial and many other applications.

Tactile sensing has had a similar development cycle but has still to move out of the laboratory and become commercially valued for its own particular features and benefits in real applications. Why is it that nearly all robots, from industrial systems to hobby robotics, still do not employ tactile sensing? Of course, many robots do use some form of crude proximity or touch device that detects contact events. But such primitive “tactile bump sensors” are binary switches that trivialize the nature of tactile sensing and do not reflect the complexity of skin-based mechanisms nor the sophistication of the many tactile arrays and other devices developed over the past three decades. On the other hand, cameras and vision sensors are now almost de rigueur for robotic systems, no doubt partly because they are so readily purchased, configured, and applied.

This paper summarizes the history and current state of the art in tactile sensing and analyzes why past predictions for the exploitation of the technology have not been realized. From observations about the trends and directions of recent research, I propose some new application areas, and their benefits and challenges, that will motivate research and development in the future.

2. The Vision of the 1980s

I define tactile sensing as a form of sensing that can measure given properties of an object through physical contact between the sensor and the object. This essentially involves an intimate relationship with the skin or bounding interface of a physical system. Examples of properties that humans can sense include temperature, pain, vibration, object shape, texture, temperature, hardness, and moisture content. It is important to note that the term “contact sensing” covers both force sensing and tactile sensing. The forces and torques experienced through points of contact with a surface are very important for manipulation and grasping tasks, which form a major research field in robotics. However, most of the tactile sensing literature deals with surface or skinlike sensors and so does not concern force/torque sensing, which has a separate history and has reached a somewhat more advanced level of

maturity. We will exclude this topic, although recognizing its importance for integrated sensing in multifingered robot hands (Howe 1994).

In the 1970s, despite a great deal of robotics activity in general, very little research on tactile sensing was performed. Some good ideas were put forward, but the few devices reported were primitive, for example, adding transducers to detect movement in compliant robot components or detecting contact through force feedback. For a comprehensive review of work in the 1970s, see Harmon (1980).

By contrast, the 1980s were a period of growth and exploration. A great variety of device designs, transduction methods, and sensing physics was examined in this period. The main transduction methods investigated include resistance and conductance, capacitance, piezoelectric and pyroelectric, magnetic, magnetoelectric, mechanical, optical, ultrasonic, and strain gauges. A typical device consisted of a surface pad with a linear or rectangular array of scalar valued sensing points.

Successful devices were built that could detect object properties such as shape, size, presence, position, applied force patterns, and temperature. Properties such as surface texture, hardness, and consistency proved much more difficult to sense, and effective solutions were not reported.

There are several reviews that survey progress in tactile sensing in the 1980s: Nicholls and Lee (1989), Dario (1991), De-Rossi (1991), and Nicholls (1992).

The prevailing view of industrial exploitation at that time could be labeled "device centered"; that is, research into new devices would lead to commercial products, which in turn, would lead to applications. Thus, the long-term justification for tactile sensing was the eventual production of "feeling" robots with rather nebulous abilities and applications. There was hardly any emphasis on a "task-centered" approach in which the design of the sensing system is crucially determined by the requirements of the task to be performed. Indeed, the application task was rarely analyzed, or even formally presented or specified.

A notable exception was the excellent work of the late Leon Harmon who carried out several studies aimed at determining the requirements for tactile sensing in industrial tasks. Through questionnaires and interviews, Harmon analyzed the perceived need for tactile sensing and the specification of tactile devices across various robotic applications (Harmon 1982). The set of requirements devised by Harmon as desirable performance specifications can be summarized (see Table 1). Harmon's work and these general requirements became widely cited as design criteria for practical tactile sensors and were often used to justify many designs.

However, Harmon's survey was necessarily speculative, and with hindsight, many of its conclusions can now be seen as overoptimistic. For example, 90% of the respondents questioned felt strongly that tactile sensing was needed in the next generation of robots. They believed that existing proximity

and force sensing would be retained but that tactile sensors would provide complementary support and additional benefits. An acknowledged bias in the study was that the work addressed predominantly manufacturers and researchers, that is, the suppliers of the technology, not the users and customers of robotics.

Much of the analysis focused on factory-based robotics and automation:

Industrial automation is clearly the area of greatest opportunity in robotics. Such operations as assembly, pick-and-place, grinding, and inspection will become increasingly more automated in the next 10 years. Touch sensing, now extremely primitive, can be expected to evolve into a highly developed technology in the near future. (Harmon 1982, p. 30)

While the prediction for increased industrial automation has certainly become true, the implication that tactile sensing has a pivotal role to play has proved false! In surveying the market opportunities, small-part assembly was seen as one of the most desirable targets in industrial automation, in terms of both payoff and demand. This was because assembly accounts for a high proportion of a product's cost (up to 30%) and is still largely performed by human operators. In Harmon (1984), the specific needs of automated small-part assembly are addressed. A set of charts was produced by Harmon showing the relative difficulties, needs, and benefits in a range of different market application areas. Across all application areas, the maturity of tactile sensing was reported as either low, very low, or zero.

Toward the end of the 1980s, although there had been no real signs of industrial take-up, most researchers (including the author) still agreed with Harmon and believed that industrial robotics would soon adopt tactile sensing:

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 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. (Nicholls and Lee 1989, p. 26)

In fact, we still do not see any significant factory-based tactile sensing, and the commercial sensors are now even less in

Table 1. Harmon's Design Criteria

Sensing Surface	Compliant and Durable
Spatial resolution between sensing points	1 to 2 mm
Number of sensing points in an array	between 50 and 200
Minimum pressure sensitivity	1 gram
Dynamic range	about 1000:1
Output response	monotonic, not necessarily linear
Frequency response	at least 100Hz
Stability and repeatability	Good
Hysteresis	Low

evidence. It seems that tactile sensing has been neglected or even rejected by manufacturing industry.

There are several reasons why the expectations for tactile sensing were raised so high. A great boom in robotics technology was under way, and sales were growing at 30% per annum. All branches of robotics research were encouraged and funded, and tactile sensing, offering much growth potential, seemed no different. There were many financially based projections for growth but very few technical analyses of application task requirements. In such a climate of optimism, Harmon's work was regularly cited to justify research work and identify the eventual beneficiaries. In fact, it was difficult to find a dissenting view, a rare example being that of workers in the Charles Stark Draper Laboratory in Boston who argued strongly that passive compliance and monitoring would obviate the need for tactile sensors (Nevins and Whitney 1977).

With hindsight, most researchers now hold a more balanced view. It is important to state that I do not criticize Harmon, who was explicit about his assumptions and cautious in his claims:

In previous years, there have been numerous projections of robotics growth in which optimistic enthusiasm often was substituted for sober accuracy. (Harmon 1982, p. 28)

One interesting result of Harmon's survey of application potential was that those applications that deal with living systems, that is, medicine, surgery, and agriculture, were considered to be the most unpromising areas as they contain too much technical difficulty to produce a return on investment. We are now seeing a significant reversal of this situation in recent research trends, and there are signs that the application market is following suit.

3. Recent Developments in the 1990s

Most of the data in this section are drawn from Lee and Nicholls (1999), which provides a comprehensive survey of the recent tactile sensing literature.

First, we notice the continued growth of research in tactile sensing. Recent findings show that the volume of material on

tactile sensing continues to grow at increasing rates. Three periods of growth are discernible, roughly corresponding to the past three decades (see Table 2).

These figures are approximate and should be taken as lower bounds. They do not include technical reports, theses, patents, and other material. They include only papers that focus on or include a major section on tactile sensors. For example, for the 1970s, the review of Harmon (1980) contains 160 references, but careful inspection shows that most deal with robotics issues rather than contributing to the technical tactile literature.

In most reviews, the literature is usually broken down in terms of broad classifications such as sensor designs and transduction technology, tactile image processing, shape recognition (especially curvature), active and haptic sensing, and architectures and integration. The work of the 1990s tends to fall into a different pattern, and Lee and Nicholls (1999) produced the taxonomy in Table 3.

The topics are ranked in activity level as calculated from the number of papers located in a class as a percentage of the total number in the survey. Topics are marked as significant recent growth areas if they have emerged or dramatically grown in the 1990s.

The most active area continues to be the design and construction of new sensors. Of course, any classification scheme is to some degree arbitrary, and sensor design could be considered to encompass both sensory data processing and analysis and experience, thus giving 40% of the activity in this dominant area. The next biggest area is active tactile sensing including haptic and integrated sensory-motor perception. This has been recognized for some time as a key area for development. Research into dexterous manipulation is closely

Table 2. Approximate Publication Rates

	1970s	1980s	1990s
Journal papers	15	55	150
Conference papers	15	60	96
Total number	30	115	246
Number per year	3	12	30

Table 3. Taxonomy Classes Ranked in Order of Activity

Topic	Activity (%)	Recent Growth
Sensor Design and Construction	20	
Haptic and Active Perception	15	
Analysis and Experience	11	X
Processing of Sensory Data	9	X
Applications: Surgery	9	X
Multifingered Hands	8	
Sensing Fingers	8	
Applications: Health Care	7	X
Probes and Whiskers	5	
Applications: Agriculture and Food	4	X
New Soft Materials	3	X
Industrial Robot Grippers	1	

related, and this involves both multifingered hands and the design of fingers themselves. These three areas combined account for 31% activity. The class for industrial robot grippers only admits advances in realistic engineering application scenarios: unusual or unproven grippers are included in Sensing Fingers. We notice the remarkable change in fortunes of this category.

From this literature survey, we can highlight some of the notable developments of the 1990s as follows.

Better Engineering and New Materials. There is a new concern for engineering issues, device packaging, and deeper understanding of sensor operation and performance. Current sensors are often silicon fabricated, with tougher, more durable designs. Many new and different materials are being examined, and much is being learned about the complexities of friction control in the human finger. Systems that can alter the characteristics of a soft contact surface show promise for future devices.

Increased Understanding of the Role of Sensors. The elastic contact layers that have been used in so many tactile sensors act as low-pass filters, preventing the detection of fine-form detail. The mathematics of this, known as the tactile inversion problem, has received much attention, and we now have several ways of dealing with such problems. Recent sensors have been produced that can detect fine-form texture, stress changes, the various stages of dynamic slip, and other temporal contact events. By using several complementary sensors with different response rates (see below), an integrated system can process a range of contact features in a given sensing problem. Also, while compliant materials have essential properties for some tactile tasks, it has been shown that rigid contact must be established if dynamic properties of objects are to be sensed through tactile means (Ellis, Ganeshan, and Lederman 1994).

Improved Dexterous Robot Hands. The manipulation of objects by multifingered hands has made considerable progress. Contact force and torque vectors are essential for fine control of manipulation tasks, but kinesthetic information alone is not sufficient, and so, dexterous manipulation requires truly integrated sensing. A mixture of tactile sensors is needed to cover a range of spatial resolutions: arrays for locating contact position and shape (low-frequency response: 0-10 Hz), stress rate sensors for fine form detail (10-50 Hz), and skin acceleration sensors for slip detection (50-1000 Hz). Other vital requirements for dexterous manipulation include high-quality real-time control (Howe 1994). Much inspiration comes from human dexterity, and increasing knowledge is gained from contributions from physiology, psychophysics, and neuroscience.

New Medical Applications. A remarkable growth of interest in tactile sensing in the medical community was reported in Lee and Nicholls (1999). New sensors for tissue discrimination and hardness/softness sensing have been produced (see Ohtsuka et al. 1997; Lindahl and Omata 1995), and further developments seem assured. The loss of tactile sensation in minimal invasive surgery (MIS) creates a real need that should provide a strong motivation for future research.

It is clear that there has been no decline in research activity in tactile sensing, only a shift away from the constrained, solid-materials of the industrial arena and toward the softer, less ordered world of natural systems.

4. The Failure to Penetrate into Industrial Applications

An often-cited goal of the work of the 1980s was to provide tactile sensors that could determine the shape and location of

objects during processing operations in manufacturing. We now consider why this opportunity was not taken up.

One reason might be that basic specifications, such as that of Harmon, could not be achieved. As Ricker and Ellis stated in 1993 (p. 941),

Ten years ago, the future of artificial touch seemed assured; desired characteristics for tactile sensors had been identified and a profusion of devices were proposed and built. However, many of these sensors had performance problems that render them unsuitable for even the simplest tasks.

This refers to the failings of laboratory prototypes that were unreliable and difficult to reproduce. There were several major engineering issues that acted as barriers to the commercialization of many laboratory systems. One example is the serious problem of wear. By definition, tactile sensors will be subject to considerable wear and tear on their contact surfaces. However, recent work is now addressing packaging and engineering issues and has produced reliable, accurate, and tough sensors. The call for “robust, accurate, and repeatable sensors” is now being answered, and so, we can no longer use these objections but must look for more subtle reasons.

In the manufacturing industries, most products are created by machining and processing raw materials and then assembling the resultant components. As the components are designed artifacts, they are fully specified and have known properties. This allows the manufacturing environment to take advantage of this knowledge and introduce many beneficial constraints in the production process. In particular, a modern processing plant aims to monitor and control the location of all components at all times. The locations of all objects are thus *predictable* (as are any shape changes). This highly structured environment then obviates any need for sensors, except for detecting error conditions. Such locative data would normally be updated through tracking but occasionally might be lost due to unconstrained operations, for example, long-duration treatment in an oven or immersion tank. In such cases, the components might emerge on a conveyor belt and their location is then to be recaptured.

In such examples, we see why other sensors, even vision, are often preferred as superior to tactile sensing. Good engineering practice dictates that solutions are often compromises between conflicting requirements, for example, performance, reliability, and cost. Simplicity is always preferred over complex solutions, and in the above example, a proximity sensor may be a better solution than either vision or tactile sensors. Production engineers have great expertise in finding efficient, elegant solutions with limit switches, proximity detectors, and other simple sensing devices, and their solutions may be shown to be clearly superior in terms of engineering criteria that treat the problem in a holistic or systems manner. In cases in which computer vision systems have been

adopted, the task criteria often specify that complex information on object shape or location is to be computed remotely, without any need for contact or manipulation, which would introduce additional operations and complications.

This engineering view explains why small-part assembly is very unlikely to be automated by the *direct* replacement of human operators by dexterous robot hands. Clearly, dexterous manipulators are essential for the full flexibility and manipulation abilities necessary to replicate human assembly performance, but is it desirable or even reasonable to tackle assembly in this way? Effective automatic assembly machines already exist, and even for a fully flexible small batch system, any such machine is very unlikely to emerge with anthropomorphic characteristics. This would ignore all the experience of the “design for assembly” methodology and would be a most unrealistic and poorly engineered solution! Robots with multifingered hands will have many important roles but not in the factory environment where much less complex solutions are likely to succeed if task analysis is properly performed.

5. New Opportunities for Tactile Sensing in Robotics

If we accept that tactile sensing may often not be the most effective option in highly structured environments, we can turn to unstructured environments and consider the possibilities for the future. Such environments range from the completely unstructured as found in the natural world to the loosely constrained, quasi-ordered frameworks found in human workplaces, such as hospitals, companies, and to a lesser extent, the home. For robotic tasks, we can distinguish three levels of difficulty: irregularities in the objects to be handled, disorder in the working environment, and both occurring together. Examples of these are food processing in a factory, underwater repair work, and surgical operations, respectively. It is notable that these are typical of the very application areas that were thought far too difficult previously. However, contact events are much more significant in these areas than in the industrial scenario, and so, tactile sensing may offer solutions that cannot be matched by other sensing modalities, such as vision.

Taking a task centered view, we now examine in Table 4 three main application areas identified in Lee and Nicholls (1999). I list their basic characteristics, which identify the main needs, and these must be satisfied by appropriate technical developments that answer the main challenges.

5.1. Surgery and Medicine

Current trends show that surgery is a very exciting and rapidly developing area in which tactile sensing is of central importance. Surgery is essentially a visual and tactile experience, and any limitations on the surgeon’s sensory abilities are most undesirable. Modern techniques and instruments, however,

Table 4. Future Application Areas

Surgery and Medicine	
Feature	Need
Very rapid take-up	Restore taction in MIS
Disposable equipment	Laparoscopy improvements
Sophisticated users	Remote palpation
Technical issue	Challenge
Telepresence	Force and tactile feedback
Teletaction	Mobility, fine control
Soft tissue discrimination	Hardness/softness sensing
Health Care and Service Robotics	
Feature	Need
Demographic projections	Personal space manipulation
Enormous demand imminent	Mobility aids
Cost reduction essential	Automated household tools
Technical issue	Challenge
Haptic exploration, dexterity	Safety
Adaptation, customization	Reliability
Low costs	User acceptance
Natural Product Processing	
Feature	Need
High volume	High speed
Human excluded environment	Inspection function
Versatile, product changes	Consistency
Technical issue	Challenge
Soft, delicate items	Active handling control
Irregular objects	Reliability
Long run-times	Hygiene

MIS = minimal invasive surgery.

can make the surgeon more remote from the operation. MIS, also known as “keyhole surgery,” is only 10 years old and yet is now routinely used as the preferred choice for many operations. Despite its many advantages, MIS severely reduces the surgeon’s sensory perception during manipulation. 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. Because the instruments are rigid rods and effectively have fixed pivots at the entry points, the available degrees of freedom are restricted and therefore impose severe additional constraints on the operator. Problems include restricted manipulation mobility, lack of depth from 2D vision, and the almost complete lack of a sense of touch. Both tactile sensing technology and telepresence are very relevant here and have much to offer in solving these problems. See Fearing, Moy, and Tan (1997) for the current state of remote tactile sensing, or “Teletaction.” I envisage future MIS systems will have many robotic features including greater mobility, force reflection, 3D monitoring, and data enhancement. It is clear that tactile sensing is greatly needed in this area,

and current trends show that researchers are responding to the opportunity.

Another reason why tactile sensing is so important in surgery is that soft tissue can only be properly examined and identified by assessing its properties of softness, viscosity, and elasticity. 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 (Cohn, Lam, and Fearing 1992). To support remote palpation (Howe et al. 1995), future surgical tools will have sensors that can distinguish different kinds of tissues by sensing properties such as elasticity and dielectric permittivity. These will be able to locate modules, tumors, abnormal stiffness of organs, and so forth, and restore sensation to the surgeon through fingertip tactile displays.

Although some experiments have been reported, it is unlikely that fully autonomous robotic systems will take over surgical procedures. I envisage surgeons retaining supervision and control but being supported by advanced robotic devices that enhance their skill and perception, reinforce safety

(by constraining the operating region), and provide better instrumentation and data. There is also much scope for new sensing instruments and a great need for restoring full freedom of manipulation during remote procedures.

5.2. Health Care and Service Robotics

Future demographic change in the developed countries will soon create enormous demands for health care and support of the elderly population. Robotics will become an essential technology in this area but will have some rather specific, unusual, and demanding requirements. The main problem is the need to operate in a human-centered environment, which contains very unstructured and irregular objects of all kinds of texture and composition. Dexterous manipulators will be important here, especially for the retrieval and manipulation of personal items for the disabled and elderly. Much progress has been made with multifingered hands that can manipulate objects with considerable dexterity. The big challenge will be in the design and engineering of such systems so that the costs can be brought low enough for the mass market.

Another aspect concerns the unique nature of each individual environment. This means that predefined functions will have a very limited role and that each system will have to be customized for the user's environment. In addition, long training sessions will not be tolerated; thus, any learning processes used will have to be based on learning-from-example techniques rather than methods that require large batches of training data. Autonomous haptic exploration is now coming of age (Okamura, Turner, and Cutkosky 1997), and this offers much promise for the learning of the user's environment.

Other important factors include high levels of human friendliness, compatibility, and acceptance. Manipulators and mobility systems for use in hospital and the home will need to be attractive and easy to use, their control and operating modes will be highly tuned to be acceptable and user-friendly, and their appearance and design will be compatible with user preferences. In addition, there must be high levels of safety and reliability as these systems will operate within the user's space, and therefore, any failure modes must always carry low risk for the user.

These features are almost the opposite of those found in most robotics work; they are certainly widely different from industrial robotics. Here we are concerned to make automation more attractive to people, have high levels of flexibility in operation, excellent user-friendliness, and near complete safety during both normal operation and failure modes. Traditional issues of accuracy and high resolution are now much less important, and some limitations in handling may be accepted if treated within the framework of a flexible learning aid. However, the overriding factor is cost—if large numbers of personal manipulation aids are to be sold, as will be needed to satisfy demand, then costs must be brought down. This is perhaps the most pressing challenge, especially for our engi-

neering and design expertise. I see great opportunities in this area and anticipate significant growth in the near future, both in research and development.

5.3. Agriculture and Food Processing

The agricultural and food production industries are heavily automated but do not yet employ much robotic or tactile sensing technology. Unlike manufacturing automation, the processing of natural produce usually involves relatively high numbers of human operators. This is because the economics of handling large volumes of soft, delicate, or varying quality items still favors humans rather than machines. Although automated handling is used for very high volumes, such as for the lower valued fruit and vegetables, for example, the intrinsic flexibility and implicit inspection skills of people still give a formidable cost/benefit equation.

However, other factors are becoming important. In agriculture, high-value produce can merit special handling, and in food factories, there is much emphasis on zero defects. To reduce hygiene risks, eliminate contamination, and prevent human errors, fully automated factories have many desirable characteristics. Such factories can operate at low temperatures throughout, which is more hazardous for people but is a better environment for food preparation.

These developments will require robotic handling systems with high sensitivity, adaptation, and dexterity. To grasp, manipulate, or process soft objects such as fruit, confectionery, and food items, robotic devices will have to sense hardness, textures, and surface properties.

Also, these natural products do not have fixed shapes but vary in their dimensions and shape considerably. Robotic grippers, whose form will be quite different from multifingered hands, will be adaptive and automatically accommodate size and shape variation. We can expect reactive styles of gripper control to be used that exhibit a variety of gripping strategies including active control of slip during object handling. Close integration of sensory-motor control will be needed, and techniques from behavior-based robotics will give the goal-direction, robustness, and adaptation needed. We expect such systems will draw on our knowledge of actuation and gripper design, and force, tactile, and spatial sensing, to produce smart soft-product handling systems with overall abilities approaching those of human operators.

The health care and natural product application areas both concern tasks that involve essential physical contact but also need information to be acquired about the nature of the contact. Although the applications are quite different, both depend on sensory information gleaned during the grasping or manipulation operations. This is important for both variable product handling and in coping with the variations found in local personal environments. Vision may also have a role to play as a remote sensor, particularly for localization and inspection, but tactile sensing will facilitate immediate adaptive

behavior in local spaces or close-coupled object/gripper systems. We can look forward to the realization of this potential and the imminent development of these application areas.

6. Conclusion

To summarize, I list some key issues and findings:

Tactile sensing has matured considerably. It is still a relatively new form of sensing but has made notable progress in the 1990s. Understanding of materials, sensor engineering, analysis, and requirements has grown considerably. New sensors are more reliable and accurate and can offer a range of response modes. The field is at least an order of magnitude smaller than computer vision technology, but research continues at increasing rates.

General shifts of emphasis. The 1990s has seen the field shift in various ways: from isolated device design toward devices in systems, from vision-type image-processing methods toward active sensing techniques, and concerning commercial offerings, from tactile arrays to the supply of components.

Tactile sensing is a complementary sensing modality to vision. It is important for the task analysis of applications to remember the key distinction: vision (and other sensors) function at a distance from the target, while tactile sensing involves direct contact. This is one of the main factors that make tactile sensing less attractive for industrial applications.

Contact tasks in unstructured environments. In any application where contact is necessary to move objects and there is some degree of uncertainty in the contact or the material of the objects, tactile sensing is a good candidate for assessment.

Dexterous manipulation. Progress with multifingered hands and haptic sensing has been very promising. Laboratory systems are now able to maintain control over objects, while rolling and sliding occurs during manipulation tasks. Autonomous haptic exploration will soon be a reality for dexterous manipulators (see Okamura, Turner, and Cutkosky 1997).

New Applications in the living world. Surgery and medicine have recently provided the motivation for a range of developments. The reliance on tactile feedback by surgeons has inspired research into restoring the tactile sense in MIS and other procedures. Other medical examples include remote palpation and new sensors for medical tactile exploration. If irregular objects are to be transported, as in food manufacture and agriculture, then active grasping with integrated sensory-motor control can provide new handling regimes for soft, delicate

produce. Even greater demand will soon be experienced for systems that operate in the unstructured personal environments found in health care and service applications.

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