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Tactile sensing and control of robotic manipulation

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Abstract—This paper reviews the current state of the art and predicts the outlook in robotic tactile sensing for real-time control of dextrous manipulation. We begin with an overview of human touch sensing capabilities and draw lessons for robotic manipulation. Next, tactile sensor devices are described, including tactile array sensors, force-torque sensors, and dynamic tactile sensors. The information provided by these devices can be used in manipulation in many ways, such as finding contact locations and object shape, measuring contact forces, and determining contact conditions. Finally, recent progress in experimental use of tactile sensing in manipulation is discussed, and future directions for research in sensing and control are considered.

1. INTRODUCTION

Human dexterity is a marvelous thing: people can grasp a wide variety of shapes and sizes, perform complex tasks, and switch between grasps in response to changing task requirements. This is due in part to the physical structure of our hands (multiple fingers with many degrees of freedom), and in part to our sophisticated control capabilities. In large measure this control capability is founded on tactile and force sensing, especially the ability to sense conditions at the finger–object contact. Indeed, people become clumsy when deprived of reliable tactile information through numbness of anesthetized or cold fingers [1].

For the last two decades robotics researchers have worked to create an artificial sense of touch to give robots some of the same manipulation capabilities that humans possess. While vision has received the most attention in robot sensing research, touch is vital for many tasks. Dextrous manipulation requires control of forces and motions at the contact between the fingers and the environment, which can only be accomplished through touch. Tactile sensing can provide information about mechanical properties such as compliance, friction, and mass. Knowledge of these parameters is essential if robots are to reliably handle unknown objects in unstructured environments.

Although touch sensing is the basis of dextrous manipulation, early work in tactile sensing research focused on the creation of sensor devices and object recognition algorithms. Particular attention has been devoted to skin-like array sensors, as exemplified by Hillis [2], who built a simple tactile array sensor and demonstrated recognition of flat objects such as washers. The creation of multifingered robot hands increased interest in tactile sensing for manipulation, beginning with preliminary work on incorporating tactile information in manipulation (e.g. [3, 4]). In the last few years studies on the use of tactile sensing in real-time control of manipulation have begun to appear. In these studies, tactile sensors provided information that guided the execution of the tasks, including automatic grasping, edge tracking, and rolling manipulation.

These experimental studies have just begun to explain the ways that tactile sensing enhances manipulation capabilities, and many questions remain unanswered. At present we lack a comprehensive theory that defines sensing requirements for various manipulation tasks. Thus, in addition to the recent experimental studies mentioned above, our knowledge of which physical quantities are important to sense for dextrous manipulation and how to sense them are drawn largely from two sources: investigations of human sensing and manipulation, and mechanical analyses of grasping and manipulation [5].

The theories presented here summarize the insights from these sources and our hypotheses for further methods of integrating tactile sensing with control for manipulation. We focus on real-time control of precision manipulation by multifingered hands, because this is the most flexible manipulation mode and places the greatest demands on touch sensing. Analysis of 'power' grasps with extended areas of contact between the hand and object is a new area of research [6], and sensing and control requirements are unclear. For reviews of tactile sensing in a more general context (including device design and object recognition) the articles by Nicholls and Lee [7] and Howe and Cutkosky [8] may be of interest. Among the books devoted to robot touch sensing are [9–12].

This review begins with an overview of human touch sensing capabilities and a discussion of the lessons for robotic manipulation. Next, we describe tactile sensor devices, including tactile array sensors, force-torque sensors, and dynamic tactile sensors. The use of these touch sensors to derive information for manipulation is then reviewed; important properties include contact location, contact force, and contact condition. Finally, we discuss the present state of the art and future directions for sensor-driven manipulation research.

2. HUMAN TACTILE SENSING

The human sense of touch has served as the main source of insight and inspiration for the development of robotic tactile sensing. The last 10 years have seen great progress in understanding some of the mechanisms underlying human taction. There is an important distinction between two different components of contact sensing in humans: *kinesthetic sensing* refers to perception of limb motion and forces with internal receptors, while *cutaneous sensing* is the perception of contact information with receptors in the skin. The kinesthetic receptors include muscle spindles, which respond to changes in muscle length, and tendon organs, which sense muscle tension [13]. There are also receptors in the joints which report joint angles and forces, although the precise role of these sensors in motor control is the subject of some controversy. In addition, deformation of the skin around each joint may contribute to the sensation of joint angles, particularly in the fingers.

Nearly all of the muscles which actuate the fingers are located in the forearm, with muscle tension transmitted to the point of action by tendons passing through the wrist. Studies of robot manipulator design suggest that transmission dynamics such as friction, backlash, compliance, and inertia make it difficult to accurately sense and control endpoint positions and forces based on actuator signals alone [14, 15]. This implies that kinesthetic information from the muscles is insufficient for good control of contact, particularly for the smallest motions and lightest forces where transmission dynamics tend to mask the desired signal. This is one explanation for the crucial role of skin sensors in measuring mechanical parameters at the contact location.

Considerable research has been devoted to detailing the function of human cutaneous sensing; Vallbo and Johansson [18] have summarized many of the pertinent results. There are four types of specialized mechanoreceptor nerve endings in the smooth skin of the human hand, as shown in Table 1. They can be categorized by two criteria: the size of their active areas and their response to static stimuli. Nerve endings with small receptive fields are called Type I units, while those with large fields Type II. Units that respond to static stimuli are denoted SA (for slowly adapting), while those with no static response are denoted FA or RA (for fast or rapidly adapting). There are about 17 000 mechanoreceptors in the grasping surfaces of the human hand, and center-to-center spacing ranges from about 0.7 mm in the finger tip to 2.0 mm in the palm. In addition to these specialized mechanoreceptors, there are many free nerve endings in the finger tip skin which respond to local mechanical deformation. Some free nerve endings are sensitive to thermal and pain stimuli. Thus our tactile sensory experience is built from a variety of sensors responding to a number of physical parameters.

Human touch can be remarkably sensitive. For shape sensing, the ability to resolve two pointed indenters on the finger tip requires that the points be separated by at least 1 mm. Humans perceive a surface as textured rather than perceiving each small surface feature individually if the features are less than about 1 mm in extent. Johansson and LaMotte [19] found that the minimum perceivable height of a static raised feature on a smooth surface was 0.85 microns. For all measurements of human tactile performance, it is important to consider that mechanoreceptor responses are strongly nonlinear and time varying. Measured sensitivity varies greatly with stimulus size, shape, and duration.

Johansson and Westling have performed a series of experiments that elucidate some of the functions of touch sensing in the performance of manipulation tasks [1, 20]. Nerve signals from each type of mechanoreceptor were monitored as subjects grasped and lifted specially instrumented objects. The experiments showed that the grasp force was always near the minimum required to avoid slipping, despite large variations in object weight and coefficient of friction of the grasping surface. Signals from the FA nerve endings indicated the earliest stages of slip [21], which were invariably followed by a reflexive and unconscious increase in the grasp force which prevented further slipping. Signals from the FAII endings indicated the making and breaking of contact between the fingers and the object and between the object and the table. More recent studies [22] investigate force sensing and muscle control during manipulation.

Table 1.
Characteristics of the specialized mechanoreceptor nerve endings in human finger tip skin (adapted from [16–18])

Receptor type	Field diameter	Frequency range	Postulated sensed parameter
FAI	3–4 mm	10–60 Hz	skin stretch
SAI	3–4 mm	DC–30 Hz	compressive stress (curvature)
FAII	>20 mm	50–1000 Hz	vibration
SAII	>10 mm	DC–15 Hz	directional skin stretch

In general, human sensing and motor control bandwidths are slow in comparison with robotic manipulators. Nerve conduction velocities are usually less than about 60 m/s. Latencies are at least 20–30 ms for the fastest reflexes and much longer for other reflexes and voluntary responses. Humans appear to rely on anticipatory or feedforward control, using open loop signals from the central nervous system that are very accurately tailored to task requirements [22]. One example is playing a fast musical passage on the piano, where there is insufficient time for feedback from tactile sensors in the finger tips to influence the muscle commands before the key stroke is completed. Humans repetitively practice such tasks to make conscious use of sensory information to perfect the required motor commands, which are then 'played back' through the fingers to accomplish the task.

Humans also compensate for slow response times by controlling the mechanical impedances of the fingers, hands, and arms [23, 24]. Impedance modulation may limit the need for feedback because the correct impedance can passively generate the appropriate response to disturbances. Experiments show that people stiffen their hands in anticipation of disturbances which might displace them [22]. There is also evidence that the damped, spring-like characteristics of the muscles themselves are vital for producing appropriate impedances for contact interactions [25].

2.1. Lessons for robotics from human tactile sensing

Several key points from the study of biological tactile sensing should be emphasized. First, there are many different types of receptors in the skin and muscles, and these sensors respond to a wide variety of stimuli. Bandwidths range from a few Hz to several hundred Hz, and sensed parameters include skin stretch, skin curvature, vibration, and muscle force and length. This suggests that creating a robot hand with dextrous manipulation skills will require a range of sensors for different parameters.

One puzzling aspect of human tactile sensing that may have important implications for robotics is the poor performance, in technological terms, of biological tactile sensors. These sensors are hysteretic, nonlinear, time varying, and slow; each nerve ending responds to a variety of physical parameters; and the 'all-or-nothing' nature of pulse-frequency encoded nerve firing obscures much of the information that is available at the nerve ending. In contrast, our experience in building robotic systems teaches us that good performance requires the use of linear, time-invariant sensors which respond to a single parameter. Perhaps the central nervous system can extract useful information from these 'bad' transducers simply because the number present in the human hand is so vast that redundant information is available. At present we do not understand the information requirements for manipulation, so it may be that the limitations listed above do not impair the sensor's ability to convey the needed information.

It seems that human reliance on feedforward control is due to the long delays inherent in nerve conduction. This is not a problem in robotics, since a controller can respond to sensed information much more quickly. However, anticipatory control may be important for robotics, too. Performance will almost certainly improve if the controller action is based on a good model of the process to be controlled. Thus the recent attention in the robotics research community to the issue of learning control, impedance control, and task modeling can be combined with sensor-driven control to provide higher levels of performance.

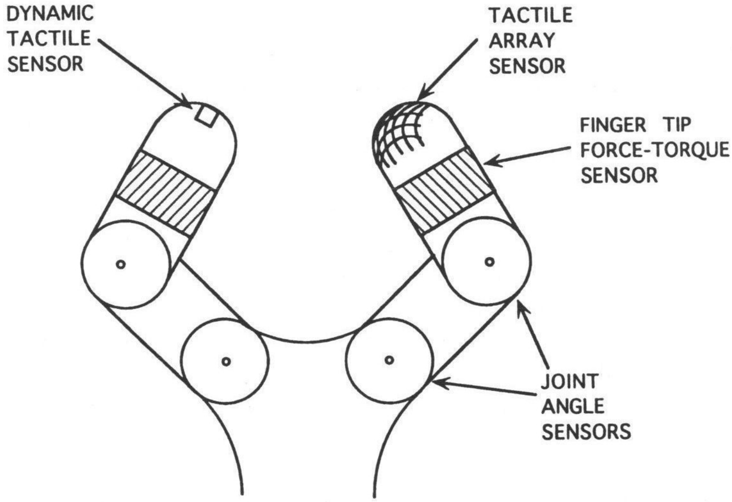

Figure 1. Schematic drawing of a robot hand equipped with several types of contact sensor.

3. TACTILE SENSING DEVICES FOR MANIPULATION

Many sensing devices have been developed for robotic manipulation. A sketch of a robot hand with some of the most common types of contact sensors is shown in Fig. 1. These sensors are the tactile array sensor, finger tip force-torque sensor, and various dynamic tactile sensors (Table 2).

The sensor that has received the most attention is the *tactile array*, which emulates the distributed sensory arrangement of human skin. These sensors typically consist of individual pressure-sensitive elements arranged in a rectangular array over the contact surface at the finger tip. As objects come into contact with the sensor, the displacement or pressure at each individual element is measured, which provides knowledge of the local surface shape and/or the pressure distribution across the contact between the robot

Table 2.
Important parameters sensed by touch, and the sensors used to measure them

Sensor	Parameter	Location
Tactile array sensor	pressure distribution, local shape	in outer surface of finger tip
Finger tip force-torque sensor	contact force and torque vectors	in structure near finger tip
Finger joint angle sensor	finger tip position, contact location	at finger joints or at motor
Actuator effort sensor	motor torque	at motor or joint
Dynamic tactile sensor	vibration, stress changes, slip, etc.	in outer surface of finger tip

finger and the object. Typical tactile array sensors have about 8×8 elements on 2–3 mm centers.

Hundreds of these devices have been described in the literature, and every conceivable transducer technology has been employed. (See [8] for a review of array sensor technologies and performance.) Piezoresistive materials are the oldest and best known transducers for tactile arrays. Pressure on the surface of the sensor causes the material to compress, which changes its electrical resistance. The materials are inexpensive, and construction techniques and readout electronics can be quite simple. However, these materials suffer from a number of problems, including hysteresis, contact noise, fatigue, low sensitivity, and nonlinear response [2, 26, 27]. Other successful transducer technologies include capacitive sensors (e.g. [28]), and optical sensors (e.g. [29–31]). Some variants of the array sensor measure only 'lumped parameters' at the contact, such as the location of the pressure centroid or contact area (e.g. [32]).

Some sensors directly measure object shape by sensing the deflection of a compliant rubber covering (e.g. [33, 34]). Others measure surface, pressure usually by sensing strain (e.g. [2, 28]). Solid mechanics models can then be used to find shape from the strain readings, although this is an underconstrained inversion problem not unlike computer vision [28]. Several schemes have been proposed for sensing multiple components of subsurface strain to improve the quality of the inversion process [35, 36]. It is frequently suggested that it is important to sense shear force distribution at the contact, although it is not clear how this information would be used in manipulation. (See the discussion of slip sensing and control below.)

Performance considerations in array design include spatial resolution, temporal resolution, pressure or shape range, accuracy, hysteresis, linearity, uniformity, and stability. A few workers have considered system-level issues such as multiplexing, packaging, and the importance of curved rather than flat surfaces [26, 37, 38]. Although the design of tactile array sensors has dominated the research literature on tactile sensing, the relationship between sensor performance and task requirements is far from clear.

Another important tactile sensor is the *finger tip force-torque sensor*. This is a multi-axis load cell mounted just behind the finger tip that measures up to three force and three torque components. This sensor does not measure the details of the distribution of contact pressure, but only the net force and torque vectors due to the contact with the object. In principle, any type of multi-axis load cell could be used for manipulator force-torque sensing. However, the need for small, lightweight units with good static response eliminates many commercial sensors. The design of force sensors for mounting behind the gripper at the wrist has received the most attention (e.g. [9, 11]), but finger tip sensors for dextrous hands have also been devised. Often these sensors are based on strain gauges mounted on a metal flexure (e.g. [3, 39, 40]). Design considerations for force sensors include stiffness, hysteresis, calibration, amplification, robustness, and mounting.

Important information about the contact can be derived from internal measurements in the robot hand mechanism. Robot hand *joint angle sensors* are used with the kinematic model of the robot structure to find the locations and orientations of the robot finger tips in a common frame of reference. From the finger tip location it is often possible to obtain the approximate location of the contact with a grasped object. Further aspects of the object shape, orientation, and location may be inferred, particularly on a large scale. Finger tip location information is also necessary to relate small-scale shape and pressure information from tactile array and finger tip force sensors to larger object and grasp models. In a similar way, it is possible to learn about contact forces from *motor torque sensor* measurements by making use of the kinematic model of the robot hand, specifically the transpose of the jacobian matrix. In this case, it is only possible to sense forces in the directions that the joints move [41]. The quality of these measurements may not be as good as those from finger tip force-torque sensors, since the intervening inertia and compliance of transmission elements and links can contribute unmodeled forces and displacements.

Dynamic tactile sensors are valuable in complex dextrous manipulation tasks. These sensors respond to *changes* in the conditions at the contact, in analogy with the fast-adapting (FA) mechanoreceptors in the human hand. These sensors often measure vibrations or changes in stress within the rubber 'skin' covering the robot finger tip. One type of dynamic tactile sensor is designed to detect when a grasped object begins to slip from between the fingers of the robot hand. These sensors can be based on detecting object motion with respect to the finger tip (e.g. [42]), or vibrations produced by slippage [65]. Other dynamic sensor uses include contact detection, texture measurement, and measurement of very small surface shapes (e.g. [43–45]).

4. TACTILE SENSING IN ROBOTIC MANIPULATION

As discussed above, we do not at present know what sorts of contact information are required for manipulation control. The specific sensing requirements certainly vary with the details of the task: a simple pick-and-place operation in a structured environment (as in many industrial assembly operations) may not require sensing of any sort, while manipulation of an unknown object with rolling, sliding, and regrasping will certainly require a great deal of contact information. One important distinction is between continuous sensing that is used in real-time control of the fingers and simple threshold detection that is used in 'guarded moves'. There have been few reports of experimental investigations of manipulation with robot hands. Thus the sources of the hypotheses about sensing in manipulation presented here are mainly human contact sensing and robotic grasp analyses (e.g. [46–48]).

The following discussion of contact sensing and control of manipulation is framed in terms of a multifingered hand grasping an object with contact at the tips of the fingers. Manipulation requires the application of forces by the fingers to produce a desired motion of the object, or to produce a net force between the object and the environment. Figures 2 and 4 show some of the ways that touch sensing can be used in maipulation. Figure 2 concerns geometric information (principally shapes and forces), while Fig. 4 concerns contact condition information.

Some of the most important means of using touch to derive geometric information about manipulation are indicated in Fig. 2. Robotic grasp analyses suggest that the most important geometric parameters to sense are the location of the contact between the robot finger and the object and the net force at the contact. These location and force measurements are needed to determine the behavior of the hand–object system using the equations of motion (or force equilibrium, in the quasi-static case). These measurements can also be used to find the grasp matrix [47], from which can be found the internal grasp forces between the fingers and the force between the object and the environment.

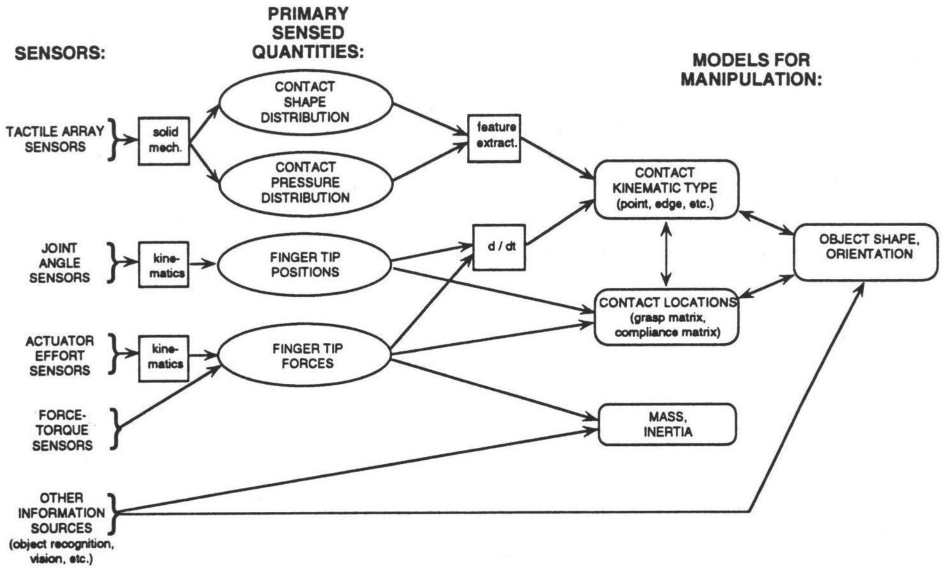

Figure 2. Uses of touch sensing in manipulation: Geometric information. Each type of sensor is shown on the left and the primary sensed quantities derived from the sensor data are indicated in the middle column. These quantities are then used to update models of the geometric aspects of the manipulation task, such as grasp configuration, object shape, contact kinematics, etc. Arrows indicate only the most important methods of deriving information; many other connections are possible. (From [49].)

4.1. Contact location

Contact location can be found in a number of ways. The fundamental measurement relies on the robot joint angle sensors, which together with the kinematic model of the robot mechanism relate each finger tip location to a common frame of reference. This is coarse information, since any contact is only localized to lie somewhere on the surface of the finger, but these measurements are essential for interrelating more specific sensor information within a common frame of reference. The contact may be further localized with a tactile array sensor. These sensors directly indicate the object shape or distribution of contact pressure across the finger tip. Knowledge of the location of the sensor on the finger surface is then combined with the finger location (from joint angle measurements and robot kinematic) to get the contact location in the global frame.

If the shape of the robot finger tip is known, Salisbury [3] has devised a scheme for determining the location of the contact using measurements from a force-torque sensor in the robot finger tip alone. This may be easily illustrated in the two-dimensional case (Fig. 3). The sensor provides a measurement of the contact force $\mathbf{f} = [f_x\ f_y]^{\mathrm{T}}$ and torque t. These quantities are related by the equation defining the torque $t = \mathbf{r} \times \mathbf{f}$, where $\mathbf{r} = [x\,y]^{\mathrm{T}}$ is the location of the contact on the finger tip. If the finger tip shape is known, we have an equation for the shape given by $g(\mathbf{r}) = 0$; for example, if the finger tip is circular, $|\mathbf{r}| = (x^2 + y^2)^{1/2} = \text{const}$. This pair of nonlinear equations may be solved for the two components of the unknown contact location, x and y. The extension to three dimensions is straightforward. Brock and Chiu [39] and Bicchi [50] present extensions and applications of this scheme. Using the same sort of ideas, Eberman

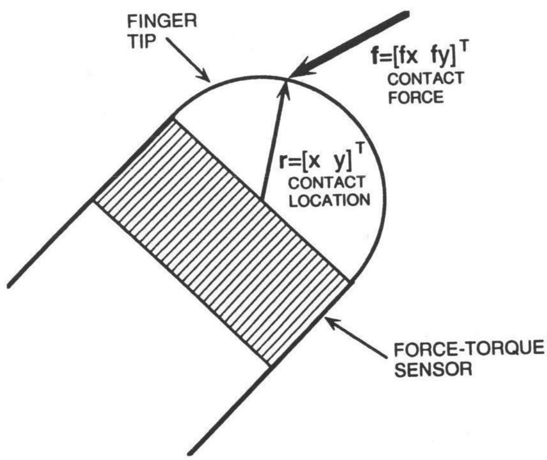

Figure 3. Sensing contact location with a force-torque sensor.

and Salisbury [41] investigated the use of motor torque sensing and kinematics to find contact locations on robotic arms.

4.2. Contact forces

Contact forces can be measured directly with finger tip force-torque sensors. A more indirect approach uses motor torque sensing together with the transpose of the Jacobian derived from the hand kinematics. In the latter case it is only possible to sense forces in the actuated directions, and the contact force measurement accuracy may be reduced by the mass, compliance, friction, and backlash of any links and transmissions that intervene between the torque sensors and the finger tip. In some circumstances it may also be possible to find contact forces (at least in the normal direction) by summing the readings of a tactile pressure array [28].

Measurements of contact location and force may be combined to permit manipulator compliance to be controlled or object compliance to be measured. Information about finger and object compliance is used to form the compliance matrix which relates forces to motions of the grasped object [51]. Force sensors can also be used to measure the object's mass and its distribution [39].

4.3. Object shape

In some tasks object shape information is important. At the largest scale, we sometimes need to know the global shape of a grasped object, as when we assemble a peg in a hole and need to know the shape of the peg tip. To find gross shape directly, the robot fingers may be used to explore the object surface in a groping mode [52, 53]. Here each contact location is correlated in a global frame of reference to find gross shape. Knowledge of object shape and orientation can obviously come also from nontouch sources such as vision, which then may be correlated with touch information.

At the next level of detail, it is important to find the local surface orientation, specifically the surface normal vector. One use of this information is to prevent slip. The ratio of the normal to the tangential force components determines whether sliding will occur. If the finger tip and the object are both convex, then the local normal direction can be determined from knowledge of the contact location and the finger tip shape. This approach breaks down if there is significant deformation of the finger tip (from indentation by the object) so the finger tip is not convex. A similar problem occurs if the contact is at a corner or edge of the object, where curvature is high and the surface normal is not uniquely defined across the contact. In this case measurement of the local curvature of the object is required to find the effective normal direction. The most straightforward way of finding local curvature is with a tactile array sensor. Another method of finding local curvature is the evaluation of changes in force-torque sensor readings after small finger motions at the contact [3].

Curvature measurements are also important in tasks that require more sophisticated manipulation operations, such as sliding the fingers or rolling an object between the fingers. An everyday example is picking up a pencil from a table and maneuvering it to a writing grasp. This shape information is needed to predict the motion of the fingers as they slide or roll over the object surface [54–56]. In many tasks it may be sufficient to classify the contact 'type' as a point, edge, or area contact, as a succinct means of describing its kinematic behavior [46].

This discussion demonstrates that a number of different sensors provide information about geometry and forces. To a great extent the scale of object and task determine which sensor is useful in a particular situation. Most grasp analyses are based on point contact models, which effectively assume that the contact area is small compared to the other length scales such as finger-to-finger distances. This approximation may be appropriate for tasks involving large objects or large tolerances. In these tasks it may be sufficient to use relatively coarse location information derived from internal sensors such as joint angle and finger tip force sensors.

Similarly, for large forces the actuator effort sensors may measure the applied forces to sufficient accuracy. In contrast, for precision tasks involving small objects or small forces and motions, tactile array sensors provide the most sensitive measurements. In general, as task requirements become smaller, sensors must be located closer to the contact so that the compliance and inertia of the intervening parts of the manipulator do not interfere with the measurement. Dario [10] suggests that finger tip force sensors are useful for forces of 0.1–10.0 N while array sensors are best used to measure distributed forces of 0.01–1.0 N.

4.4. Pressure distribution

Aside from its use in determining curvature, pressure distribution information is important in sliding. To prevent unwanted slips requires estimating the largest forces and torques that the contact friction can sustain without slipping. Likewise, to plan or control sliding manipulation it is important to be able to predict the relationship between sliding motion and applied forces and torques. For pure translation, the force required to cause slip is simply given by the coefficient of friction times the total normal force; under the usual Coulomb friction conditions this is independent of the details of the pressure distribution. To find the torque required to make the contact start to slip in rotation, however, requires pressure information: if the pressure is concentrated in a small area, then the contact can sustain less torque before slipping than if the pressure is distributed over a wider area.

If both translation and rotation are occurring, the relation between the force and torque is complex. Several methods for calculating these friction limits have been developed [57, 58]. These calculations require measurement of the coefficient of friction, the total normal force, and the normal pressure distribution. Then the combinations of total shear and torque that will cause slip can be calculated, along with the direction of the resulting motion. Alternatively, if a given sliding motion is desired, the required shear and torque can be calculated. Measurement of the coefficient of friction can be accomplished through vibration sensing [59, 65] or by inducing small slips and measuring resulting force vectors with a finger tip force-torque sensor [60]. These methods suggest that it is not necessary to sense shear force distribution across the contact to control or avoid slip.

4.5. Contact conditions

Figure 4 shows how touch information can be used to learn about contact conditions such as phase changes, local friction, and slip. During manipulation, fingers can start

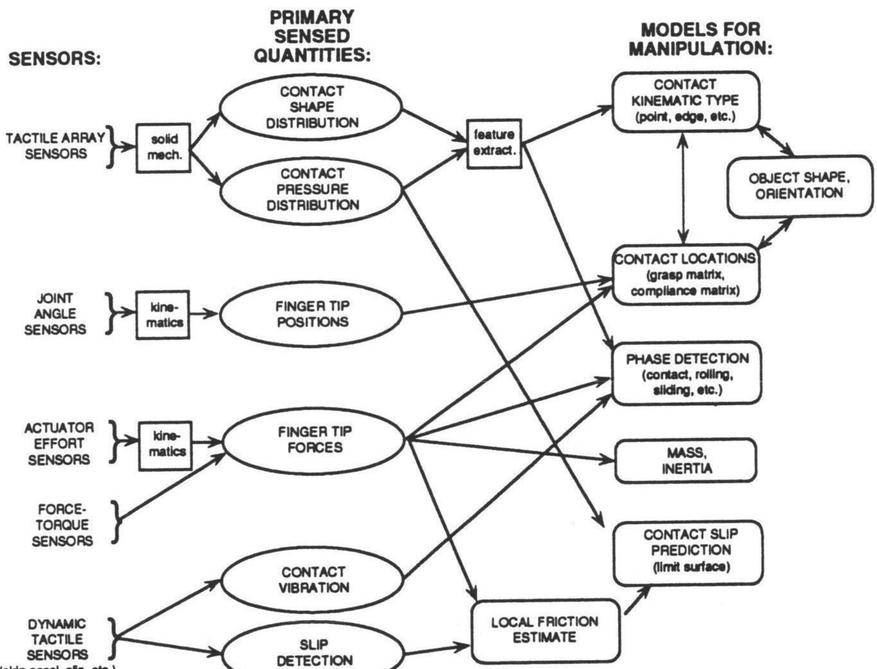

Figure 4. Uses of touch sensing in manipulation: Contact condition information. Each type of sensor is shown on the left and the primary sensed quantities derived from the sensor data are indicated in the middle column. These quantities are then used to update models of *contact conditions*, such as local friction, slip limits, contact phase (making and breaking of contact, rolling, sliding), etc. Arrows indicate only the most important methods of deriving information; many other connections are possible. (From [49].)

to roll, pivot, or slide, and make or break contact with the grasped object. These events are important to detect because they denote a transition between fundamentally different phases of the task, each of which may require a different planning and control strategy [61]. For example, in grasping an object the positions of the fingers must be controlled before they contact the object, but after contact the forces need to be controlled, so each of these phases requires a different controller.

Information about these transitions or phase changes can come from a variety of sensors. For example, the displacement of an edge between successive tactile array 'images' can reveal rolling or sliding of the object over the finger. Another example is contact detection. It is possible to detect when a finger makes contact with an object surface by sensing the presence of a contact force (finger tip force-torque sensor), the cessation of joint motion (joint angle sensor), the presence of a contact pressure distribution (tactile array sensor), or the presence of impact vibrations at the contact (dynamic tactile sensor). Some of these indicators are preferable because they are faster or more reliable, depending on the particular phase change. Thus pressure distribution information is not the best indication of contact because array sensors are usually multiplexed and thus relatively slow.

5. DISCUSSION AND CONCLUSIONS

5.1. The current state: examples of touch sensing in manipulation control

One encouraging sign of progress in tactile sensing research is the appearance in the last few years of the first experimental investigations into the use of tactile information in real-time control of manipulation. Four significant examples include edge following with a tactile array [62], contact state detection using dynamic tactile sensors [61], manipulation with rolling contact based on array information [56], and automatic grasping using finger tip force-torque and palm sensors [63]. In each case touch information was used as the task progressed to generate trajectories and forces appropriate to changing task requirements.

While emulation of human tactile sensing has unquestionably led to useful insights, it may also have led to misdirections in robotic tactile sensing research. From robotic analysis and experimentation it appears that the most important parameters to sense in manipulation are the location of the contact and the net contact force. Humans apparently sense small forces via cutaneous perception, particularly with SAI and SAII nerve endings [18]. The desire to emulate human skin has produced an emphasis on tactile array sensors in robotics research. However, as described above, contact location and contact force information can be successfully obtained from force-torque sensors as well as from arrays. Since force-torque sensors are far easier to build and their signals are easier to interpret, it would seem that these sensors deserve greater attention from robotics researchers. A similar motivation to copy the human design may have led to the often-stated need for array sensors for shear force distribution, even though slip analysis does not predict a need for such information.

5.2. Future directions

One of the most important points in tactile sensing for robotic manipulation is the absolute necessity of good control of forces and fine motions. It is impossible to get a useful signal from a tactile sensor if the manipulator to which it is attached cannot provide smooth control of contact. Since tactile sensors provide information which facilitates smooth contact, there is an 'initialization problem': good tactile signals require smooth control and smooth control requires good tactile signals. This means that robot hands must be designed with sensing requirements in mind, and sensors must be developed for specific manipulators and tasks. One promising development is the Bologna hand [64], which has elaborate sensing designed as part of the entire hand system including six-axis force-torque sensors on each link of each finger. This may permit far better control of forces than with the usual *ad hoc* addition of sensors after the design is complete.

In robot hand design, the near-ubiquitous use of tendons passing through sheaths to transmit power from motors to finger links is frequently the limiting factor in control of forces. Contact between the tendon and sheath causes backlash and friction, producing dead zones where forces and motions cannot be controlled [15]. Until the transmission problem is solved, it will be difficult to achieve good manipulation performance with multifingered robot hands. Possible solutions include the use of sophisticated sensing and control schemes to compensate for the undesirable characteristics of tendons (or gears), or the development of new transmission devices without these undesirable properties.

A systems-level understanding is needed both within the contact sensing system and for the entire manipulator system, encompassing sensor, structural, and controller elements. Integration of touch sensors with manipulators will require accounting for such factors as multiplexing and addressing, bandwidths, dynamic range, etc. Another critical issue is the increasingly elaborate software necessary to incorporate tactile information into real-time control. A vast number of contingencies can be encountered in complicated tasks and a complex sensor system will be required to differentiate them. But even if we succeed in creating sensor systems that can acquire the appropriate information, at present we have little idea of how to structure a control system to use this information.

The importance of and appropriate values for many of these factors cannot be assessed without experimental testing in real manipulation tasks. Thus the greatest task facing touch sensing research is experimental evaluation of the role of touch sensing in manipulation. Once we have created manipulation systems that can respond to information from a range of sensors, we can begin experimental testing that will reveal the combination of sensors and sensor-driven control strategies needed for machine dexterity. We might speculate that a fundamental set of sensors for precision tasks might include joint-angle sensors, six-axis finger tip force-torque sensors, and vibration sensors.

Application areas where touch is important will include contact tasks, where small forces and displacements must be controlled. Such tasks are at present beyond the capability of even laboratory robots and industry understandably avoids these tasks whenever possible (thus the emphasis in product design on 'design for manufacturability'). In the long term it may be useful to have industrial robots perform tasks which require a good sense of touch, but until researchers understand the basic issues it seems unlikely that industry will find much use for them. Unstructured environments such as undersea and space exploration, hazardous material handling, and household robotics will more likely find a need for touch sensing.

5.3. Conclusion

Ten years ago a commonly-cited impediment to progress in tactile sensing was the lack of suitable tactile sensing devices and algorithms for interpreting tactile signals. Adequate devices and low-level signal processing techniques have now been demonstrated, and we have made a good start at understanding how touch can be used to provide information about a variety of geometric and mechanical properties of the environment. The primary issues in touch sensing are now concerned with the integration of these devices and algorithms into practical manipulation systems that combine sensors, controllers, and manipulators. The next step will be the expanding use of these systems in manipulation experiments to ascertain the information requirements and appropriate role of touch sensors in dextrous robotic manipulation.

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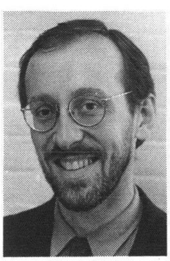

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