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14

Robot Tactile Sensing: Skinlike and Intrinsic Approach

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1. INTRODUCTION

An intelligent robot is not a speculative machine: its primary task is to acquire knowledge and to interact with its environment. The part of the robot that is designed to physically realize such interaction is its end-effector, which plays the same role of the hand in the human arm; end-effectors can assume different forms, from a simple gripper to an articulated mechanical hand.

Talking about hands is not inappropriate in a book dedicated to intelligent robots: the relevance of gripping devices to intelligence can be illustrated by considering how the evolution of animals in more and more intelligent species corresponds to the increasing sophistication of their grippers, from jaws, tentacles, and claws to hands.

It could be observed that, in the artificial intelligence (AI) and robotics communities, much more attention has been devoted so far to the role of artificial vision than to perceptual aspects of manipulation. This probably depended on the availability of accurate and relatively economic vision sensors (television cameras). Moreover, even though an ideal vision system would be able to dynamically analyze scene details (Albus, 1981), processing static images is often sufficient to extract several interesting features of a robot's environment.

Unlike vision, touch requires sensors mounted on parts of the robot itself to be intrinsically active, that is, implying coordinated sensorimotor actions to explore the environment: in a sense, it can be affirmed that the real touch organ is not the tactile sensor, but the whole hand. Moreover, tactile information can be elicited only by contact, and this is intrinsically dangerous for the robot's and touched objects' integrity. These facts, together with the unavailability of adequate commercial devices, initially hindered investigations of tactile perception. However, the important contribution of tactile information to perceptual processes, both as a substitution for vision (e.g., in scarcely illuminated environments) and as a complement (to indicate hidden features of objects in the visual field or to confirm hypotheses suggested by vision), encouraged a continuously growing interest on artificial touch (see, e.g., Bajcsy, 1983; Stansfield, 1986; Dario and Buttazzo, 1987).

The evolution of robotic hands in artificial touch organs has two main aspects: mechanical dexterity and sensorial capabilities.. In fact, to allow the robot to acquire and apply knowledge in an unstructured and a priori unknown world, flexibility and sensibility of the end-effector are fundamental prerequisites.

Looking at the state of the art of robot hands, we can observe an almost discouraging lack of these characteristics. Industrial robots often employ special-purpose tools as end-effectors for particular operations (such as spray painting or spot welding); a wider scope of tasks (e.g., pick-and-place or assembling) is accomplished with very simple grippers, similar to pincers, able only to open and close. In a very few cases such grippers are equipped with sensors for detecting contact or proximity with an object. Much more sophisticated robot hands can be found in research laboratories: several articulated hands with up to 16 degrees of freedom, more or less reproducing human hand structure (assumed as a well-proven example of successful design), have been developed since 1975 (Skinner, 1975); at present, prominent realizations are the JPL/Stanford hand (Salisbury, 1982) and the Utah/MIT hand (Jacobsen et al., 1984). However, even in such advanced hands the sensorial apparatus is not yet satisfactory.

This chapter is devoted to the analysis of the physical and conceptual link between robot hands and intelligence: tactile sensing. We present two possible approaches to the design of contact-sensing devices for robot end-effectors, skinlike and intrinsic, provide a brief survey of the state of the art, and illustrate respective pros and cons; in some cases, sensors integrating both principles are shown to obtain synergistic results.

2. INFORMATION FROM TACTILE SENSING

By the term "tactile sensor" we mean in general a device capable of collecting information about contact phenomena occurring between the robot end-effector (usually on parts called fingertips) and the surroundings. Although the important role of tactile sensing is almost unaminously recognized in robotics, the characteristics that a tactile sensor should have are not equally clear. Specific features a tactile sensor should be sensitive to are not definable a priori but strongly depend on the task the robot is intended to perform and on the type of end-effector with which the robot is equipped. Nevertheless, it is possible to identify some types of information that a tactile sensing system should provide to allow the hand to perform fine manipulation tasks:

1. Force information: Sensing the intensity and direction of both forces and torques exerted through contact between the end-effector and the manipulated object is instrumental to any fine manipulation operation. To measure the friction component of contact force may also be very important to prevent slippage of objects held by the hand.
2. Synthetic geometric information: The position of the contact area on the fingertips and the direction of the common normal vector to the contacting surfaces represent essential information for manipulation control and can also be very useful for object recognition.
3. Local geometric features: Information about the extension, shape, and indentation profile of the contact area allows the extraction of small (compared to fingertip dimensions) features of the explored surface, such as edges, vertices, and cavities.
4. Texture, friction, and thermal properties: Other peculiar characteristics of the explored surface can be sensed by touch, such as its superficial roughness, friction, temperature, or thermal conductivity.

Detecting all these types of information may require a number of different sensors, each specialized to extract a specific feature of the environment. During active exploration and execution of manipulative tasks, simultaneous real-time acquisition of sensory data is required to adaptively control robot motion and to immediately react to external stimuli. On the other hand, each sensor involves different preprocessing and purposely designed algorithms to extract the feature of interest; an independent processing unit may hence result, necessary to handle the information produced by a sensor. Although a detailed analysis of computer architecture for active perception and sensory data fusion is out of the scope of this chapter, it is worth observing that parallelism and hierarchical organization in processing and control are required. A deep discussion of the general philosophy of a sensor-based architecture for controlling highly sensorized systems can be found in Albus (1981); for example; from the implementational point of view, some special-purpose computer architectures for controlling multisensor robot systems dedicated to tactile perception have been proposed by Goldwasser (1984) and Kriegman et al. (1985).

3. SKINLIKE TACTILE SENSING: A SURVEY

A skinlike tactile sensor usually consists of an array of sensing elements, each providing local information about the contact between sensor and environment. In analogy to vision systems, a single sensitive site of the array is often called a "taxel" (tactile element), and the global information coming from the whole matrix is called a "tactile image" (Dario and DeRossi, 1985).

The conversion of applied forces into measurable electric signals may involve different technologies. In this section we discuss the most common technologies employed for building skinlike tactile sensors.

3.1 Piezoresistive Sensors

A piezoresistive transducer is characterized by modulation of its electrical resistance with the applied load: piezoresistive materials commonly utilized in tactile sensing are conductive elastomers, that is, rubbers or foams that can be easily deformed under load. If electrodes are placed on the faces of a sample of a conductive elastomer, the resistance variation caused by electrodes approaching under load can be easily measured. Several experimental devices based on this principle have been developed since 1981 (Purbrick, 1981); a common arrangement of such sensors consists of two sets of parallel conductive rubber stripes placed at right angles, taxels being formed at each intersection. The commercially available Sensoflex tactile system produced by Barry Wright Co. consists of 256 taxels whose centers are spaced 2.5 mm apart. Conductive elastomers have several favorable features, such as low cost and good conformability; the bandwidth of the single taxels as an individual load cell is also good. Unfortunately, they suffer from high hysteresis and low sensitivity; moreover, taxel spacing in most of the proposed sensors is not satisfactory.

3.2 Piezoelectric Sensors

Piezoelectric materials generate an electric charge when mechanically stimulated by pressure. This behavior is well known to be characteristic of crystals, like quartz, but common piezoelectric materials are too fragile to be used in tactile sensors. Piezoelectric polymers are more suitable to such use; they are durable, economic, and flexible enough to conform to the curved surface of a robot finger.

Dario et al. (1984) describe a sensor that utilizes PVF_2 (polyvinylidene fluoride, a piezoelectric and pyroelectric polymer) sheets, intended to reproduce the sensory features of human skin (Figure 1). Besides pressure distribution on its surface, this sensor was able to exploit the pyroelectricity of PVF_2 to elicit information on a material's thermal properties. The device has 128 taxels spaced 3 mm center to center and arranged in a 8 × 16 array. A curved version of the sensor, shaped like a human fingertip, is described in Buttazzo et al. (1986).

Piezoelectric materials-based tactile sensors are fairly linear and very sensitive; a major disadvantage is their high-pass filter behavior, which cuts off the static component of applied load.

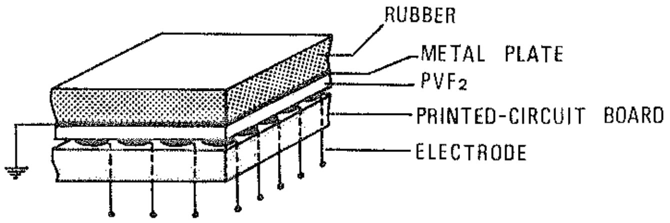

Figure 1 The piezoelectric and pyroelectric polymer (PVF_2) film-based skinlike tactile sensor proposed by Dario et al. (1984).

3.3 Optical Sensors

Light modulation techniques as applied to tactile sensing are at present studied with interest owing to the insensitivity to electrical interference of optical signals. Various mechano-optical conversion mechanisms can be devised to realize such sensors: partial obstruction of light beams by means of elastic diaphragms located in front of the photodetectors (see the commercially available Lord Corporation's sensor described in Dario and DeRossi, 1985), for example; modulation of light beam intensity through forces applied to a flexible membrane on which the light reflects (Schneiter and Sheridan, 1984); and light frustration at the interface of a light guide with deformable elements (Begej Corporation's sensor described in Begej, 1986).

For example, Begej's sensor obtains 1 mm center-to-center spacing among the taxels and outputs the tactile image on a coherent bundle of optical fibers to be read by a television camera.

The encumbrance of fiber bundles and the high precision required in sensor construction are the main disadvantages of this technology, although it will undoubtedly benefit from future progress in integrated optics.

3.4 Electromagnetic Sensors

Hackwood et al. (1983) proposed a magnetic-based sensor consisting of an array of magnetic dipoles embedded in an elastic medium. Under this rubber sheet surface, a corresponding array of magnetic field sensors detects variations in the field caused by medium deformations. The sensor has the potential to detect both normal and tangential components of applied load.

Magnetostriction, that is, stress-related magnetic anisotropy, has been used to build tactile sensors by Luo et al. (1984); the point in using this technique is that no moving elements are employed, thus enhancing sensor robustness and durability.

Common drawbacks of magnetic-based sensors are their nonlinearity and high sensitivity to extraneous electromagnetic fields.

3.5 Capacitive Sensors

A capacitive sensor measures applied pressures through the capacitance variation due to a change in the distance of two electrically conductive plates. Such a sensor is usually realized by sandwiching a dielectric layer between two sets of parallel conductive traces, with the top etches perpendicular to the bottom: at each intersection a capacitor is formed.

Siegel et al. (1986) realized a capacitive-based sensor with rather fine taxel spacing (2 mm center to center) and good linearity and sensitivity; the sensor has been designed to fit in the fingertips and fingerpads of the Utah/MIT dextrous hand. The major shortcoming of capacitive tactile sensors is their sensitivity to electromagnetic disturbances.

4. INTRINSIC TACTILE SENSING

In his paper "Interpretation of contact geometries from force measurements," Salisbury (1984) pioneered an entirely new approach to contact sensing. Bicchi and Dario (1987) proposed the name "intrinsic tactile(IT) sensors" to design devices for contact sensing inspired by this approach, that is, based on the measurement of the force-torque resultants of the distributed contact pressure. An IT sensor consists of a six-axis force-torque sensor situated inside the fingertip of the robot end-effector, whose surface, unlike a skinlike sensor surface, is not sensorized. Figure 2 shows the conceptual scheme of such a sensor mounted on the finger of an articulated hand and in contact with a generic object.

To easily understand the principle of IT sensing, it is useful to recall some basic concepts of contact mechanics.

We consider conforming and nonconforming contacts: two solid bodies brought into contact without appreciable deformations touch first at a point (or along a line) if their surfaces do not fit exactly together, and this case is referred to as nonconforming contact (e.g., a sphere on a planar surface). On the other hand, if the bodies have conforming surfaces near the contact over a finite portion of surface even if the net contact force is very small (e.g., a cube placed with its face on a plane).

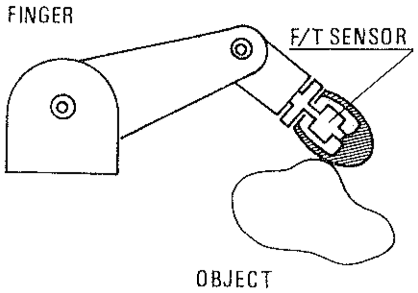

Figure 2 Conceptual scheme of an intrinsic tactile sensing fingertip mounted on a robot finger and touching a generic object. Note the ellipsoidal fingertip surface enclosing the force-torque sensor.

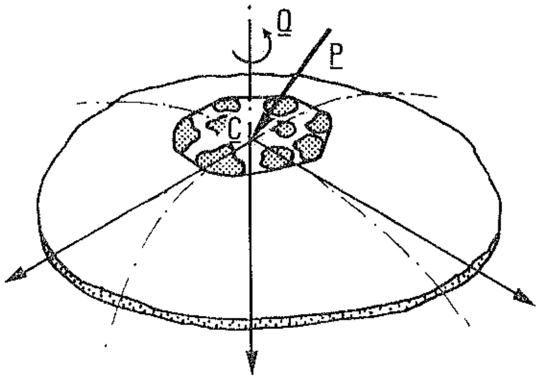

Figure 3 The minimum contact convex encloses all the small surface patches (shaded) where actual contact occurs. Only one of the contacting surfaces is shown. The contact pressure distribution is equivalent to the resultant $\underline{P}$ applied at the centroid $\underline{C}$ plus the torque $\underline{Q}$.

Even in nonconforming contacts, when the bodies are pressed together with a finite force, contact points are actually infinite (otherwise, since a single point has zero area, pressure on it would be infinitely high) and they cluster in (small) surface portions. For both conforming and nonconforming contacts, we define minimum contact convex as the smallest convex surface portion containing all contact points (Figure 3).

Two hypotheses are assumed in the following, which are often verified in contacts relating to robotic manipulation:

1. Only compressive forces are exerted by the contact (no adhesion between the two bodies).
2. The minimum contact convex approximately lies on a plane (contact plane).

The second hypothesis allows us to consider both nonconforming contacts and conforming contacts provided that the minimum convex is small compared to the curvature radii of the surfaces. For instance, the contact of a curved fingertip of an articulated robot hand with a convex body is nonconforming, thus acceptable; the conforming contact of a coin on the planar jaw of a robot pincer is still acceptable; a ball-and-socket type contact may not be acceptable with these hypotheses.

We define contact centroid $\underline{C}$ as the point of the contact plane such that the distributed contact force system is equivalent to a system consisting of its resultant force $\underline{P}$ applied at $\underline{C}$ plus a torque $\underline{Q}$ about the direction normal to the contact plane. It can be demonstrated (Bicchi, 1989) that this point exists and is unique, and that, in the preceding hypotheses, it always belongs to the minimum contact convex.

The position of the contact centroid on the fingertip surface is sufficient to locate the area where the contact occurs; this synthetic geometric information is especially valuable for small contact areas but retains value for conforming contacts. Force information on contact are contained in the resultant vectors $\underline{P}$ and $\underline{Q}$; since the application point of $\underline{P}$ on the fingertip surface is known, it is possible to evaluate its normal (compression) and its tangential (friction) components. Comparing those values and considering the friction coefficient between the contacting bodies' materials, the stability of contact against slippage can be assessed. Analogous considerations hold for the torque caused by friction forces $\underline{Q}$.

Salisbury (1985) showed that if a six-axis force-torque sensor is fixed to one of the contacting bodies (the fingertip) whose surface geometric description is known, information about $\underline{C}$ and $\underline{P}$ can be obtained with fairly good approximation. Bicchi (1989) has provided a closed-form exact solution for $\underline{C}$, $\underline{P}$, and $\underline{Q}$ for force-torque-sensorized fingertips with ellipsoidal surface (including limit cases of spherical, cylindrical, and plane fingertips).

Implementation

The basic contact mechanics underlying intrinsic tactile sensing can be implemented in rather simple devices. As already mentioned, the active part of an IT sensor consists only of a six-axis force-torque sensor. A multiaxis force sensor is in general a transductor device capable of measuring several components of the force and torque that result from a generic load on the sensor itself: a six-axis or force-torque sensor is a multiaxis sensor that measures all the six components necessary to completely characterize the statics of the load.

The development of force-torque sensors was initially fostered by the need for real-time measurement of loads varying in intensity and direction in such fields such as adaptive cutting of metals, wind-tunnel testing, or thrust stands for rocket engines. However, much research in this field has been done since the 1970s, with the impulse of growing robotic applications: several different force-torque sensors have been designed to be mounted on robot arms, mostly at the wrist (Scheinmann, 1971; Watson and Drake, 1975). A few force-torque sensing wrists are at present commercially available.

The vast majority of force sensors so far designed and applied are based on extensometry, that is, on the measurement of the strains caused by the load on the sensor structure. In fact, very accurate, reliable, and economical strain gauges (mechanoelectrical transducers that can be glued to the sensor mechanical structure and whose electrical resistance varies as the strain varies) are currently available.

Since the application of force-torque measurements to tactile sensing was only proposed in 1985, not many sensors have been designed thus far to fit the fingertips of a robot hand. Of course, miniaturization of the sensor is the major issue in this case; robustness, light weight, economy, and above all accuracy are other concerns of the designer.

The first force-sensorized fingertip was presented by Brock and Chiu (1985). The force-torque sensor is realized with 16 strain gauges applied on the four legs of a Maltese cross, built in a unique block of stainless steel; the arrangement of the strain gauges on the legs of the cross is such that their signals can be simply combined to give a decoupled measurement of the six components of force-torque.

The analysis of error propagation in a force sensor based upon linear algebra and numerical computation methods led Bicchi and Dario (1987) to present an innovative force-torque sensor whose design privileges is simplicity: the sensor structure consists of a thin hollow cylinder, and only six strain gauges (the minimum necessary number) are used to measure load components. A computer-aided optimal design technique has been employed to choose design parameters to optimize sensor accuracy according to the condition number criterion thoroughly discussed in Bicchi (1989). Sensitivity and accuracy results comparable to those of more complex and expensive sensors have been obtained with this sensor, whose dimensions are slightly larger than those of a human fingertip.

5. PROS, CONS, AND SYNERGISM

Skinlike and intrinsic tactile sensors represent two valid sources of information that can be utilized to solve a large number of problems; although some features can be detected by both sensors, they have very different characteristics. A detailed analysis of those characteristics follows.

Spatial resolution

In skinlike sensors, spatial resolution represents the minimum distance between two distinct taxels in the array. Although technological improvements in sensor fabrication may permit us to realize rather high resolution sensors, it should be considered that the large number of connecting cables and/or long acquisition and processing times represent inherent limitations to the practical use of very high resolution sensors in real-time applications. On the other hand, intrinsic tactile sensors can locate the contact centroid with very high precision. Since there is a continuous mapping of measured load components to contact centroid position, resolution of IT sensors is theoretically infinite; their accuracy is obviously limited by measurement errors of the force-torque sensor.

Multiple contacts

Multiple contacts occurring on the sensor surface are allowed with IT sensing only as far as hypothesis 2 of Section 4 is verified. Contact zones at a distance comparable to sensor surface curvature radii may render meaningless the IT sensor readings; this can be easily understood if a fingertip squeezed by two equal and opposite forces is considered (Figure 4): since the resultant force-torque is null, no information can be provided by the IT sensor. However, it can be noted that multiple contacts on a curved fingertip do not frequently occur in usual manipulation operations. Obviously, skinlike tactile sensors easily deal with multiple contacts.

Bandwidth

As noted before, bandwidth requirements for a skinlike tactile sensor conflict with resolution demands. At every sampling cycle the signal of all the taxels must be acquired and processed with rather complex algorithms to extract information significant for the control of the robot hand. Perceptual tasks, like feature extraction or recognition, involve even more complicated processing that practically excludes their execution in real time.

IT sensors, on the other hand, are much faster, since both the number of sensing elements is much lower (typically ranging from 6 to 16) and signal processing is very simple: sampling rates of about 100 Hz are easily achievable even with general-purpose electronic and processing equipment.

Force feedback

Force control is a fundamental issue in fine manipulation operations, such as grasp, micromotion, and exploration of objects, could not be executed at all by a robot hand without the capability of controlling interaction forces with manipulated objects. Although theoretically it is possible to realize such control with open-loop schemes or by using only joint torque feedback, direct and accurate measurements of contact forces are necessary in truly dexterous robot hands.

Skinlike tactile sensors are not, in general, good for force sensing because of limitations in measurement accuracy of each taxel as an individual load cell; moreover, the reconstruction of overall load from integration of local contact pressures is badly affected by low resolution of the sensor. IT sensors measure contact force with the same accuracy of the force-torque sensor they incorporate, which is usually very good.

A particularly important aspect of force measurement is friction.

Friction forces and torque

Except the pioneer work done by Hackwood et al. (1983) and Domenici et al. (1989), which has not yet been applied in practical devices, skinlike tactile sensors are not able to sense the tangential (friction) components of contact force. In some cases (for piezoelectric film sensors, for instance) friction forces may even cause signal aliasing. IT sensors are able to measure each contact force-torque component with the same accuracy, hence friction effects are properly handled.

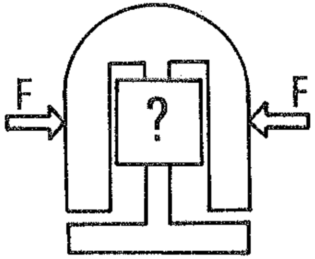

Figure 4 An IT sensor cannot detect multiple contacts like the one shown here, since it is based on resultant force-torque measurements.

Slippage prevention

One of the most important potentials offered by friction sensing is slippage prevention. The maximum tangential force $\underline{F}_t$ that can be resisted by friction forces is expressed by the Coulomb relation

$$\underline{F}_t \leq \mu_s \underline{F}_n$$

where $\underline{F}_n$ is the normal component of contact force, and μ_s the static friction coefficient.

If μ_s is known and the components $\underline{F}_t$ and $\underline{F}_n$ are monitored during manipulation, it is possible to sense impending danger of slippage and counteract this tendency. Methods for measuring μ_s directly in operating conditions and for adaptively grasping with IT sensors mounted on articulated hands are presented in Bicchi (1989) and Bicchi et al. (1989).

The ability of IT sensors also to measure friction torques can be useful to prevent another type of possible slip motion, that is, spin slip. Spin slip occurs for instance when an object held by two opposite fingers rotates about an axis passing through the fingers, overcoming friction. In this case, the maximum torque that can be resisted by friction cannot be as simply expressed as in translational slip, since it depends, in addition to μ_s, on the punctual distribution of contact pressures over the contact area. Although for curved fingertips a simple formula (Howe et al., 1988) can be used to evaluate such a maximum resistable torque (which can be compared with real-time IT measurements of actual torques to assess contact stability), this is not true for large contact areas on planar fingers. An integrated sensing system for planar fingers of a robot gripper, consisting of an IT sensor and a piezoelectric skinlike sensor, was shown to permit spin slip prevention in Bicchi et al. (1988).

Sensor surface

Skinlike tactile sensors have in theory no particular requirements for sensor surface shape or material compliance. Yet in practice only a few multi-element sensors with a double-curvature surface have been realized so far (Buttazzo et al., 1986; Begej, 1986), and cylindrical tactile sensors have been proposed by Fearing et al. (1986), for example.

Contact centroid localization on IT sensors relies on precise knowledge of the analytic description of sensor surface, which to avoid excessive computation should correspond to a simple mathematical function. As for fingertip compliance (a desirable quality for fine manipulation), both types of sensors allow it only to some extent.

Tactile imaging

By tactile imaging we mean the capability to extract local features of the touched body from a single sensor reading. For instance, the human finger is able to detect the presence of an edge on a surface simply by touching it.

IT sensors obviously lack this capability, which is characteristic of skinlike sensors. A robot hand whose fingertips are equipped with IT sensors can compensate for this limitation by resorting to active tactile sensing, that is, creating an image from several measurements carried out in the vicinity of the feature of interest; sensorimotor coordination of a hand's actuators and sensors is necessary in this case. As already mentioned, though, in humans tactile sensing is also mostly an active sense, involving dynamic exploration of objects' surfaces more than pure static imaging.

Paratactile sensitivity

A few skinlike tactile sensors incorporate sensing elements capable of detecting some very useful paratactile characteristics, such as thermal or even chemical properties of the object being touched (see, for instance, Dario et al., 1984, and Siegel et al., 1986). No such capability is provided by IT sensors, unless specific transducers are added to their basic scheme.

Encumbrance

From a practical point of view, one of the worst shortcomings of skinlike tactile sensors is the large number of connecting cables they require. Especially in articulated hands, those cables may seriously hinder manipulative dexterity. On the other hand, IT sensors connections are simple but they tend to have a rather bulky structure to incorporate the force-torque sensor.

CONCLUSIONS

Based on the analysis of respective advantages and disadvantages, it results that skinlike and intrinsic tactile sensing application domains do not coincide:

IT sensors are essential to provide feedback for low-level, real-time control of manipulation.

Skinlike tactile sensors are suitable for perceptual tasks because of their ability to form tactile images even without active exploration of the environment.

A more detailed evaluation of the specific suitability of the techniques can be made by distinguishing the type of fingertip where the tactile sensor is to be mounted:

Curved fingertips, which are typical of articulated, dexterous robotic hands: in this case, being contact areas normally small, IT sensors are sufficient to provide most of the information needed for fine manipulation.

Planar fingertips, typical of parallel jaw grippers: in addition to synthetic IT measurements, information about contact area extension and shape is fundamental in this case. Hence, integration of both types of sensors in each fingertip is recommended; as mentioned before, Bicchi et al. (1988) showed that information not obtainable from either of the two sensors alone can be extracted from an integrated device, demonstrating effective synergism of the sensing methods.

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