Tactile sensing in intelligent robotic manipulation – a review

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Abstract
Purpose – When designing hardware and algorithms for robotic manipulation and grasping, sensory information is typically needed to control the grasping process. This paper presents an overview of the major grasping and manipulation approaches and the more common hardware used to obtain the necessary sensory information.
Design/methodology/approach – This paper presents an overview of tactile sensing in intelligent robotic manipulation. The history, the common issues, and applications are reviewed. Sensor performance is briefly discussed and compared to the human tactile sense. Advantages and disadvantages of the most common sensor approaches are discussed. Some examples are given of sensors that are widely available as of today. Eventually, some examples of the state-of-the-art in tactile sensing application are presented.
Findings – Although many sensor technologies and strong theoretical models have been developed, there is still much left to be done in intelligent grasping and manipulation. This is partly due to the youth of the field and the complex nature of safe control in uncertain environments. Even though there are impressive results when it comes to specific examples of advanced manipulation, there seems to be room for great improvements of hardware and especially algorithms when it comes to more generic everyday domestic tasks.
Originality/value – This paper presents a review of sensor hardware while also giving a glimpse of the major topics in grasping and manipulation. While better hardware of course is desirable, the major challenges seem to lie in the development and application of grasping and manipulation algorithms.

Keywords Robotics, Materials handling, Sensors

Paper type General review

1. Introduction

To pour and bring a glass full of milk is an almost trivial task for a human adult. For a robot on the other hand, it is a challenging task. Nonetheless, for robots to be useful as service agents at home, in hard to reach places, hazardous areas, outer space, and elsewhere, they need to be mobile and able to grasp, move, and manipulate objects in their surroundings.

Usually, we define two different kinds of grasps; power grasps and precision grasps. Power grasps are typically used for larger objects and in tasks that do not require more than simple manipulation of the object. Grasping a chair to lift it is an example. Significant for a power grasp is that the object is fixtured by the palm and as much finger area as possible.

More delicate objects are typically held in a precision grasp. When lifting a glass and in other precision tasks, primarily the fingertips are used for contact. The precision grasp has advantages such as enabling better control of contact forces, but it is also typically less stable than the power grasp.

To perform more complex tasks such as rotating the object, as in actually pouring something in the glass, we need to be able to control the motion of the object. Using a power grasp, this can be done by moving the arm and wrist. In a precision grasp, this can be done by moving only the fingers.

The objective in using tactile sensing in robotic grasping and manipulation is to extend the possibilities beyond those resulting from using other sensor modalities only. Usually the limiting factor is lack of information (and knowledge of how to use it). Only by touch can we collect information from the very point of contact. Lee and Nicholls (1999) define a tactile sensor as "a device that can measure a given property of an object or contact event through physical contact between sensor and object." In robotic manipulation we are primarily interested in the mechanical properties of the contact. Other properties, such as temperature and moistness, will not be covered in this paper.

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First, we need to know whether we are in contact with the object or not. Seemingly simple, but we can already here see why visual information – with a comparatively low resolution, and which also can be occluded – needs to be complemented with more detailed contact information.

Second, tactile information can inform on the contact configuration. We can sense forces and torques and from that find out what type of contact it is. A surface, an edge, or a point contact will all give different pressure patterns in a sensor matrix. The vibrations that slip in a contact will cause, can be detected. Then there is haptic exploration; by moving the finger, we can extract data from several points and use that data to create or improve an object model. From that contact information it is possible to derive information regarding the object's inherent properties: – Is the object stiff or is it compliant? – Is there any texture? – What is the friction coefficient? All this information can be used to improve the object model and to improve manipulation quality.

Finally, contact data can be used as feedback for control. For complicated tasks in uncertain and dynamic environments, open loop control will not suffice. Knowing the contact properties and whether contact has occurred is essential in work with contact transition issues. The feedback can be used to control force and torque at a specific contact location, something necessary for manipulating objects and to control slippage.

As can be seen, we need a tactile sense for intelligent robotic manipulation. This paper will give an overview over the most common issues and topics in grasping and manipulation. To put things in perspective, a historical overview is presented followed by a section on likely applications. After that, a review of sensing issues starting with a reflection on the human tactile sense and how it relates to robotics. Partly because we can use it as benchmark, partly because the human sensory system and manipulation capacity is both a grand challenge to mimic and also a great source of inspiration. A review of some sensor hardware follows and eventually some examples of experimental results.

2. Historical overview

In the 1970s, tactile sensing for robotic applications emerged as its own field of research. Research kept increasing during the next decade and led to one of the first overview papers on tactile sensing by Harmon (1984). The 1980s was also time for the first advanced robotic grippers such as the DLR ROTEX gripper (Dietrich *et al.*, 1990). It is equipped with laser range finders, tactile arrays, force/torque sensors, integrated actuator, and also analog and digital electronics for communication over a serial bus, all neatly packaged in one single device.

In some areas, there has been great progress since Harmon's article from 1984. But to a large extent, the problems today remain similar to what they were back then. He foresaw a rapid expansion within automation. This however, has not been the case. Lee addressed this very fact in 2000 (Lee, 2000) when he pointed out that in structured environments, we are able to come very far without tactile information. Hence, he foresees that tactile sensing will be most useful in unstructured environments where object properties and/or the environment is not fully known.

The review paper of Lee and Nicholls (1999) gives an overview of tactile sensing in mechatronics up until 1998. The yearly number of published papers had steadily increased, an increase that has continued since then and which is exemplified by the development of novel tactile arrays manufactured in a silicon processes (Kane *et al.*, 2000), that control is evolving (Okamura and Cutkosky, 2001), and that system integration is taken to a new level (Butterfaß *et al.*, 2001).

The focus has somewhat shifted over the years; from the development of new tactile sensing technologies towards data processing. At the same time, strong theoretical models of contact configurations and grasp dynamics have been developed (Bicchi and Kumar, 2000). However, when it comes to the application of such models in association with tactile sensors, only little work has been done.

Tactile sensing for robotics is still in its infancy. While researchers in visual recognition or tracking can buy out of the box cameras (Lee and Nicholls, 1999), there is to our knowledge no widely available tactile sensor suite for robotic manipulation. There are some robotic hands out there. A few of them are available as commercial products. Unfortunately, those hands do not come cheap due to the large engineering effort and small scale manufacturing. In our opinion, there is still a need for qualified manipulation hardware and also for more advanced methods actually using the tactile information.

3. Applications

Today, much attention is given to tactile sensing in minimally invasive surgery, keyhole surgery. The case is that much of the tactile information available in open surgery, will now be lost. Artificial tactile sensing can restore some of this loss of tactile information. Eltaib and Hewit (2003) give an overview of tactile sensing in minimally invasive surgery (MIS).

But MIS still involves humans in the feedback loop and hence does not cover all needs for performing intelligent robotic manipulation. Outside the laboratory, manipulation is still primarily performed without tactile sensing. In an industrial setting, most variables can be controlled. Even though force/torque sensors are used for grinding operations and for peg-in-hole tasks, the really large benefits with a refined tactile sense can be reaped outside such well controlled environments.

For a versatile robot in an uncertain environment, tactile sensing will open up new possibilities. Recently we have seen some impressive humanoids, if they cannot be made to interact with their surrounding, they will be of little use. Combining these humanoids with advanced grasping and manipulation capabilities, has for long been a dream that opens up possibilities limited only by imagination. Such robots could be used pretty much anywhere in which it can be cumbersome or dangerous to use humans; as 24 h household help, for fire-fighting, in deep space missions or for ABC warfare clean-up.

But even without advanced humanoids, there are certain applications for which tactile sensing can be of great use and that also stand out as the most likely to be the first to apply it. Perhaps the most common justification for developing robots for autonomous grasping and manipulation is the demographic situation. Within a few decades, many industrialized countries will face a significant increase of elderly people. A robot could, for example, be used to perform simple fetch and manipulation tasks. Picking up something that has been dropped, opening the door, and working as an interface to other machines around the home are some examples of what such a robot could do (Plate 1). The challenge is to make these robots safe, useful, versatile, user-friendly, reliable, and while perhaps not cheap, at least give good value for the money. In a dynamic and uncertain environment, such as in a home not particularly modified for robot access, this becomes a truly challenging task.

Toys have previously been an underestimated market and may very well turn out to be the first robotic manipulators with a tactile sense to hit the market. Further, Lee (2000) considers natural product processing, such as agriculture and food processing, as yet another probable application area. He also gives a nice overview of the features, needs, issues, and challenges in the above applications.

4. Sensing

4.1 Human sensing

The information quality needed to perform certain robotic manipulation and grasping tasks still remains unknown (Lee and Nicholls, 1999). Neither is it known exactly how humans manipulate objects. Even if we did know, it is not certain that an anthropomorphic approach would be the best. But there is still much to be learned from what is known about the human sensory system.

A condensed overview of human sensing is presented by Howe (1994). He puts tactile sensing in perspective from a human mechanoreceptor viewpoint. To fulfill all robotic tactile sensory needs with a single type of sensor is difficult, if not impossible. This is a problem that we humans also have. To overcome it we are equipped with different types of receptors. The fast adapting (FA) mechanoreceptors can sense vibrations but not static stimulation, whereas the slowly adapting (SA) mechanoreceptors respond to static stimuli. The different properties of human cutaneous mechanoreceptors are shown in Table I.

Without visual feedback, humans have a rather dim perception of the position of their limbs. This is because the human proprioception[1] is poor, especially compared to what can be achieved in a robot. Even without visual feedback, a robot can – due to high resolution encoders – identify its position and orientation in space much more accurately than humans. This is an advantage that can be exploited, particularly in certain haptic exploration tasks (Okamura and Cutkosky, 2001).

Plate 1 Fetching some pasta

Compared to a robot, humans also respond to sensory information with a large latency. For the fastest reflexes we see latencies of 20-30 ms and much longer times for voluntary responses (Howe, 1994).

4.2 Passive and active sensing

Sensing can be divided in many ways. But one of the more important dividing lines is that between passive and active sensing. Passive sensing concerns the analysis of static tactile data, whereas active sensing is when motion is actively used to extract more information. Okamura and Cutkosky (2001) write "Some types of features, particularly small ones, cannot be sensed accurately through static touch; motion is required". An example is detecting edge sharpness. Placing a finger on the edge will give only little information regarding its sharpness compared to sliding it across the edge.

A dextrous hand can also actively manipulate its environment to retrieve information on properties impossible to estimate in other ways. For example, by tilting an object weight or center of gravity can be estimated. By dragging a finger along a surface, friction and texture can be approximated, and so on.

5. Sensors

5.1 Sensor specification

There is of course no single sensor that excels with respect to all design criteria. The sensor specification will have to depend upon the task at hand. For this reason, a very large amount of tactile sensing technologies have been developed. But some criteria that always must be considered are (Lee and Nicholls, 1999):

- variables and measurable range – pressure, shear forces, torques, slip, etc;
- resolution in space; and
- response profile – accuracy, bandwidth, hysteresis, creep, aging, etc.

In addition to these, we should add some desirable properties such as simple mechanical integration, low power consumption, and low cost.

Humans have a resolution in the fingertips of about 1 mm and are able to sense frequencies close to 1 kHz (Howe, 1994). A similar specification is often proposed for distributed tactile sensors, for example a spatial resolution of 1-2 mm and a frequency span up to at least 100 Hz (Liu *et al.*, 1995).

5.2 Sensor types

As mentioned, many tactile sensor technologies have been proposed over the years. Tactile information from a power grasp can be collected using distributed sensors covering the phalanges. A fingertip is typically more roomy and allows for a more space consuming force/torque sensor that can supply detailed information in the case of a precision grasp. The basic principles for a few different fingertip sensors can be seen in Figure 1. An excellent overview of tactile sensing devices for manipulation was written by Howe (1994). Saad *et al.* also present an overview of current sensor technologies

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Table I Different human mechanoreceptors

Receptor type	Field diameter (mm)	Frequency range (Hz)	Postulated sensed parameter
FA I	3-4	10-60	Skin stretch
SA I	3-4	DC-30	Compressive stress (curvature)
FA II	>20	50-1000	Vibration
SA II	>10	DC-15	Directional skin stretch

Source: Howe (1994)

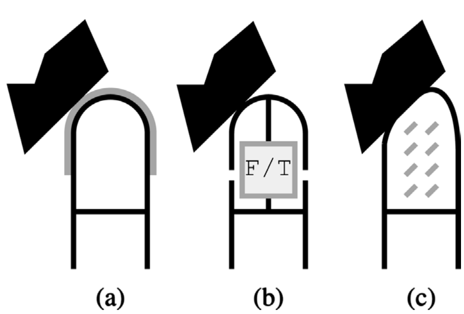
(Saad *et al.*, 2000) although omitting "image recognition" sensors such as those developed by Ferrier, Hristu, and Brockett (Hristu *et al.*, 2000, Ferrier and Brockett, 2000) (Section 5.4).

Some argue in favor of a compliant fingertip. An issue for a stiff fingertip is that it is more prone to contact transition problems and it also offers poor grip. This can to a certain extent be overcome by covering the sensor with a soft material. But more important, a compliant fingertip – not unlike the human – is also advantageous from a pressure distribution and stability point of view (Russell and Parkinson, 1993; Brockett, 1985).

If we consider the very compliant fingertips (see Section 5.4) as one sensor type, the remaining sensors can be divided into extrinsic sensors (see Section 5.3) and intrinsic sensors. The intrinsic sensors measure forces within the grasping mechanism whereas the extrinsic sensor measures forces that act upon the mechanism. The predominant intrinsic tactile sensor is a small force/torque sensor mounted inside the fingertip (Butterfaß *et al.*, 2001; Gao *et al.*, 2003). Extrinsic sensors are significantly more diverse, covering different kinds of single point and distributed sensors. Examples include force sensitive arrays to be mounted on the fingertip and those where the sensor module itself constitutes the fingertip.

The choice of whether to use extrinsic or intrinsic sensing depends upon the task at hand. The advantages of an extrinsic sensor include that they can be made to cover large areas – as when using a power grasp – and that the point of contact is explicitly measured. Most extrinsic sensors only measure pressure. But there are a few advanced extrinsic sensors capable of measuring shear forces on the tactile element level (Kane *et al.*, 2000; Yamada and Cutkosky, 1994). An intrinsic sensor using strain gauges is typically more accurate and is often designed to measure all six degrees of freedom. But there is also a larger mass, often the fingertip itself, between the object and the intrinsic sensor. This can be a disadvantage when measuring small forces and it also makes the sensor sensitive to high accelerations. An additional downside is that when using a force/torque sensor inside the fingertip, we cannot tell the difference between multi-point and single-point contacts (Okamura *et al.*, 2000). Nonetheless, intrinsic sensing is often used in manipulation tasks using a precision grasp.

Figure 1 Different fingertip sensors. (a) Distributed – extrinsic; (b) force/torque – intrinsic; and (c) fluid filled



Using an intrinsic sensor it is possible to determine the contact location without measuring it explicitly. Data from a six DOF force/torque sensor inside the fingertip can be used to compute the point of contact (Salisbury, 1984). Bicchi (1990) mathematically discusses the issues in computing contact position based on intrinsic sensor data.

5.3 Extrinsic sensors

The typical extrinsic sensor is a tactile array, not unlike a laptop touch-pad, or a single-point pressure sensor. It typically senses normal forces and contact positions. The sensors often display a measurable resistance change as a result from compression of a semi-conductive polymer.

As an example, the Gifu hand (Kawasaki *et al.*, 1999, 2002) is equipped with tactile sensors covering the phalanges of all fingers (3×5) and the palm with a grand total of 624 measurement points. The fingertips are not covered by the distributed sensor and instead feature six DOF force/torque sensors.

An optical waveguide will show nearly no loss of light if properly designed. But when its boundary is affected by touch, frustrated total internal reflection will occur. The intensity changes can be measured either by a position sensitive detector or through positioned optical fibers and separate detectors (Begej, 1988; Maekawa *et al.*, 1997).

Other measurable properties include birefringency effects resulting from internal stress (photoelasticity) (Saad *et al.*, 2000) and capacitivity changes resulting from compressing the insulator of a capacitor.

5.4 Highly compliant sensors

A fingertip exploiting the compliant and optical properties of closed cell polyurethane foam was recently developed by Hellard and Russell (2002). Also recently, the deformation of a fingertip membrane filled with a transparent liquid was measured using a camera (Hristu *et al.*, 2000; Ferrier and Brockett, 2000). The picture data were then used to compute the displacement of the membrane and from that the object shape information was derived.

5.5 Data processing

The amount of tactile data from many and large tactile arrays can be overwhelming, and even if it can be managed, just getting it to a processor may be difficult. Consider a 16×16 tactile array; a minimum of 32 electrical wires are needed. Add to this the data from 256 sensors that need to be

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Table II Small force and/or torque sensors

Sensor	Maximum force (N)	Maximum torque (Nm)	∅ (mm)	*H* (mm)
BL Nano 5/4	50	0.4	18	32.8
ATI Nano 17	50 ($F_z = 70$)	0.5	17	14.5
Bokam Aura/Supra	42 ($F_z = 153$)	N/A	24-36	5-23
FSR®	varies	N/A	>5	0.2-1.25
DLR F/T digital	30	0.15 ($M_z = 0.05$)	20	16

processed. As always, one has to prioritize, or try to come up with innovative designs.

DLR deals with this by distributing the A/D-conversion and signal processing. An example of this is their six DOF fingertip sensor (Table II) that features integrated electronics for signal processing. The sensor has a purely digital interface (Butterfaß *et al.*, 2001). Other force/torque sensors typically deliver analog signals that require an external signal processing unit.

It is also possible to perform the signal processing in the analog domain or in the sensor itself. Or simply be satisfied with not retrieving all information possible from a contact position. One example is the *XYZ*-pad (Liu *et al.*, 1995) that only needs four electrical wires and still supply normal force and *XY*-position. Tactile patterns will be impossible to recognize, and the sensor will also handle only one contact point. But for certain applications, that may suffice.

Yet another way to reduce the wiring is to use wireless communication. Optical communication from sensors embedded in a soft fingertip is proposed by Yamada *et al.* (2002).

5.6 The tactile inversion problem

When using a compliant sensor or fingertip, there is usually some elastic material or liquid between the deformed surface and the sensor array. Given the surface deformation, forward computation will give the sensor stresses. However, the other way around is more difficult and especially so in the presence of noise. Lee and Nicholls (1999) gives an overview and Nowlin (1991) discusses ill-posedness and ill-conditioning when trying to compute surface deformation from sensor data.

5.7 Widely available sensors

Today, there are many suppliers of sensors that can be used in tactile sensing for robotic manipulation. A few of them and some of their products are presented below as examples of what performance-wise well known hardware is widely available. Hopefully the number will steadily increase by the addition of complete integrated tactile systems, additional robotic hands for dextrous manipulation, drivers, and hard- and software needed to implement tactile sensing in real life applications.

Interlink Electronics, Inc. supply force sensing resistors (FSR®), both as arrays and as single element sensors like the ones in Plate 2. A matrix based sensing system is available from Tekscan, Inc. Pressure Profile Systems, Inc. market a tactile system featuring a capacitive array. (For physical reasons, such a capacity based system has a limited spatial resolution. The minimum tactile element spacing is 2 mm.) The companies mentioned above also supply other kinds of sensors, from single point sensors to conformable arrays.

Capacitive and resistive sensors often feature creep, hysteresis, and/or poor long time stability. But they are typically easy to implement and sometimes offer an accuracy high enough to make them very useful. Nonetheless, strain gauge based sensors, such as force/torque sensors, typically perform better with respect to these issues.

A miniature six DOF force/torque sensor for use in a fingertip (see Plate 3) is offered by ATI Industrial Automation, Inc. BL Autotec market a similar sensor. While not commercially available, the DLR sensor is anyway included in the summary in Table II. The force/torque sensors above are all equipped with overload protection. See Table II for example specifications.

6. Tactile sensing implemented

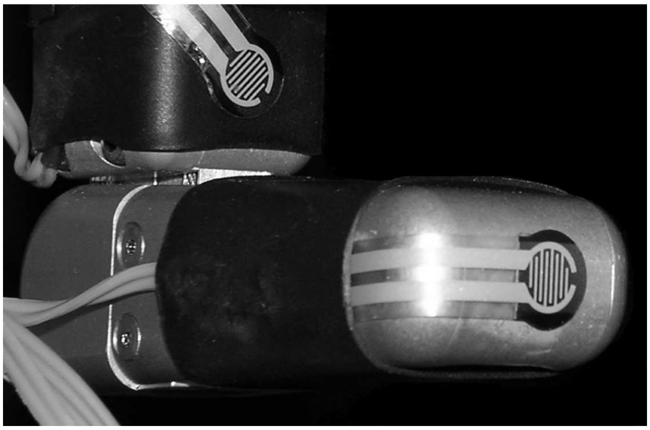
Even though there is a gap when it comes to actually manipulating objects using tactile information, as mentioned in Section 2, more and more work is being done. Bicchi (2000) presents an overview of grasping where he mentions that one of the most needed advances in robotic grasping is to estimate object compliance. Coelho *et al.* (2001) have developed models for grasp policies and grasp control and also verified them in simulation. Below are a few examples of real life experiments that until recently have been presented.

By combining tactile sensing with vision, Hosoda *et al.* (2002) present a system that learns to detect slip from tactile sensor information. Using information from an intrinsic sensor, Bicchi *et al.* (1989) present a nice method to reduce the risk of slippage by controlling the normal force.

Laschi *et al.* (2002) present an anthropomorphic robotic grasping platform developed for evaluation of neurophysiological and other physiologically inspired theories such as biologically-inspired grasping coordination. A neural approach to software development will be used.

Plate 2 The ATI Nano 17 six DOF force/torque sensor (Courtesy of ATI Industrial Automation)

Plate 3 Force sensing resistors, one mounted on the fingertip and the other on the proximal phalanx on the finger of a Barrett hand



The DLR hand is one of the most refined robotic hands of today. Both with respect to mechanics and control. It has demonstrated the catching of a ball, playing the piano, and more (Borst *et al.*, 2003). They have also implemented impedance control essential to more autonomous tasks.

7. Conclusions

Although many sensor technologies and strong theoretical models have been developed, there is still much left to be done in intelligent grasping and manipulation. In particular, there is a gap in applying the theoretical models in association with tactile sensing.

In the past, progress has been slow and it will likely stay that way for a while. But the applications, in humanoids and other applications, are closer than ever. The humanoids of today can walk and dance, but they can only perform very simple manipulation tasks. On the road towards more advanced manipulation lies many interesting challenges.

From a technology standpoint, with more and more research being published, better hardware, more powerful computing, the current development in MEMS and wireless solutions, and an increased interest from commercial players and academia, the conditions for growth and advance are better than ever.

Note

1 Proprioception – The ability to sense the position, location, orientation, and movement of the body and its parts.

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