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Review

Tactile sensors for robotic applications

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ABSTRACT

In this paper, the authors look at the domain of tactile sensing in the context of Robotics. After a short introduction to support the interest of providing robots with touch, the basic aspects related with tactile sensors, including transduction techniques are revisited. The brief analysis of the state-of-the-art of tactile sensing techniques that follows provides indicators to conclude on the future of tactile sensing in the context of robotic applications.

Contents

1. Introduction

It is perhaps difficult to agree on what a robot is, but most people working in Robotics probably would say like Joseph Engelberger, a pioneer in industrial robotics, that "*I can't define a robot, but I know one when I see one*". According to the International standard ISO 8373, a robot is "*an automatically controlled, reprogrammable, multipur-*

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pose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications". This definition, not particularly of our liking, is clearly more restrictive than for instance the one of the Cambridge Advanced Learner's Dictionary that states that a robot is "a machine used to perform jobs automatically, which is controlled by a computer". This last definition is in our opinion too poor because it does not imply something that, also in our opinion, is intrinsic to the robot concept: the inclusion of elements to gather information of the robot's environment, i.e., sensors. Potentially disputable is the need of a robot to have the possibility of action choice based on sensing information.

It is well known that industry tends to implement the easiest solutions because, in general, they are the more robust and cheaper. To do this, the industrial environment tends to be well structured and the robots used tend to follow a pre-defined program, leaving little or no room for decision making. Without the aim of advancing a proposal for a definition, we think that one can say that the characteristics of a robot or robotic system include the existence of a computer, of sensors and of mechanical or electromechanical parts actuated by actuators the whole being programmed to perform a particular job. Thus, robots come in many different shape and sizes and aim many different applications. From simple domestic devices to human replicas used at home, in industry or medicine, the abilities of robots are quite diverse, which means also different sensing requirements.

Taking the human being as a paradigm, science has long been trying to provide robots with the five basic human sensing capabilities: hearing, sight, smell, taste and touch. Each of these senses is important to a human and has domains in which it is fundamental. It is thus only natural to provide a robot with an equivalent sensing ability when it is aimed at replacing a human in a task requiring or advising the use of a particular sense.

In the following paragraphs, we will look into the sense of touch in general and into the sensors that have been developed to provide robots with tactile perception, in particular. We will give our vision about the future of tactile sensing in Robotics based on the past and present evolution in the domain. We call the reader's attention to the fact that we do not consider this paper to be a review paper. From the several reviews and overviews on tactile sensors and Robotics [1,2] and to a lesser extent [3–6] do provide a good insight and are thus recommended for reading.

2. Tactile sensing

2.1. Basic concepts

There are several robotic applications requiring or advising the emulation of human skin sensitivity to pressure. For robotic applications, the two main research areas on tactile sensor development are related with object controlled lifting and grasping tasks and with the ability to characterize different surface textures.

Tactile sensors, i.e., devices that respond to contact forces, are used for touch, tactile and slip sensing. Contrary to force and torque sensors used to measure the total forces being applied to an object, tactile sensors are devices able to measure the parameters that define the contact between the sensor and an object, i.e. a localized interaction. Touch sensing consists in the detection and/or measurement of a point contact force. Tactile sensing consists not only in the detection and/or measurement of the spatial distribution of forces perpendicular to an area but also on the interpretation of the corresponding information. Tactile sensing implies, thus, an array of a coordinated group of touch sensors. Slip sensing involves the detection and/or measurement of the movement of an object relative to the sensor. There are sensors specially designed for this purpose but the information can also be obtained by the interpretation of the data from a tactile sensor. When the tactile information is displayed as a colored picture (e.g. fingerprint identification) the sensor is usually named tactile image sensor.

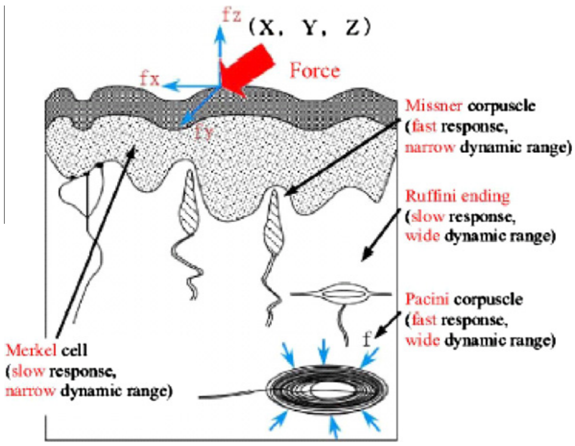

Fig. 1. Human tactile receptors [13].

Robotic applications do often require more than tactile perception. Object shape and surface roughness recognition or grasping and sliding information are only possible if both sensory and motor systems are used so as to provide haptic perception. Haptic perception is not only more hardware demanding but also much more software dependent than tactile perception: the performance of a haptic system is highly determined by signal processing and sensors' data fusion implemented algorithms. This important aspect is beyond the scope of this paper. Enlightening information on what has been recently done can be found in [7–12].

The human touch, distributed all over the body, is supported on four kinds of tactile receptors (mechanoreceptors) distributed in layers in the skin as shown in Fig. 1 taken from [13]: the Meissner corpuscles, the Merkel cells, the Ruffini endings, and the Pacinian corpuscles.

Meissner corpuscles are a type of mechanoreceptor responsible for sensitivity to light touch. They are distributed throughout the skin, but concentrated in areas especially sensitive to light touch (e.g. the fingertips). A little deeper in the skin one can find Merkel cells. They are associated with sensory nerve endings, when they are known as Merkel nerve endings. They are the most sensitive of the four main types of mechanoreceptors to vibrations at low frequencies, and because of their sustained response to pressure, Merkel nerve endings are classified as slowly adapting. Ruffini endings are also a class of slowly adapting mechanoreceptor sensitive to skin stretch, and contribute to the kinaesthetic sense and control of finger position and movement. Like Ruffini endings, Pacinian corpuscles are found in deep subcutaneous tissue, and detect deep pressure touch and high frequency vibration. They are rapidly adapting receptors, which means that they respond when the skin is rapidly indented but not when the pressure is steady.

Even if some attempts have been made recently to mimic the behavior of human touch [13,14], robotic applications rarely use tactile sensing and when they do, the sensors used tend to be as basic as possible. This is particularly true in industrial environment, since it is well known that simple, reliable, and durable solutions are better and cost less than complex solutions. Thus, tactile sensors for robotic applications have been generally designed as an array of touch sensitive sites, each usually called tactel, taxtel, texel or sensel in analogy to a pixel (picture element) in an image sensing array. It is based on the contact forces measured by the sensor that the large amount of information required to determine the state of a grip is obtained. Texture, slip, impact and other contact conditions generate force and position information that can be used to assess the state of a manipulation.

In what concerns the transduction principle used to implement the taxel, the number of implemented solutions is high. In tactile sensing, we are in the domain of force (or pressure) measurement and so most of those solutions are common to normal force transduction. It is important to mention here that, (a) in most cases, the implementation of a tactile sensor was and still is very application oriented, which also accounts for the reduced number of industrial and general purpose robots incorporating them, (b) that the operation of a touch or tactile sensor is very dependent on the material of the object being gripped, and (c) that, generally speaking, the sensing solutions that are very briefly discussed next may work quite well with rigid objects but often require modifications to adapt them to operate with non-rigid materials.

2.2. Tactile sensors: transduction principle; classic implementations

Tactile sensors are based but not confined to the following transduction principles:

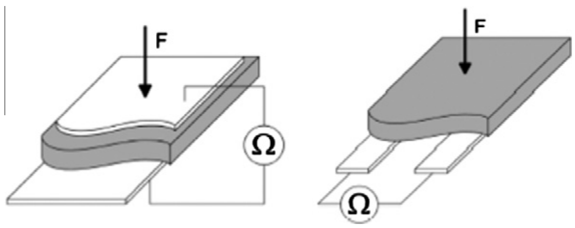

Fig. 2. Resistive tactile sensors [15].

1. *Mechanically based sensors*. Each taxel is a mechanical micro-switch that is in one of two states, on or off. The force required to switch it on depends on the switch actuating characteristics and on external constraints. Some mechanical based sensors use a second device, such as a potentiometer or a LVDT to provide a voltage proportional to the local force (pressure).
2. *Resistive based sensors*. The basic principle of this type of sensor is the change of electrical resistance with pressure of a material placed between two electrodes or in touch with two electrodes placed at one side of the material (Fig. 2 taken from [15]). One solution to implement this pressure sensitive resistor is using a conductive elastomer or foam or elastomer cords laid in a grid pattern, with the resistance measurements being taken at the points of intersection. The conductive elastomer or foam based sensor is relatively simple but (a) has a long nonlinear time constant. In addition the time constant of the elastomer, when force is applied, is different from the time constant when the applied force is removed; (b) the force-resistance characteristic of elastomer based sensors is highly nonlinear; (c) they have poor medium and long-term stability because of the migration of the resistive medium of the elastomer and to its permanent deformation and fatigue. In spite of these limitations, elastomer-based resistive sensors have been quite popular because of the simplicity of their design and interface to a robotic system.

Resistive taxels can also be made using conductive polymers and thin semi-conductive coating (ink). In the first case, the polymer is made piezoresistive by screen printing it with a film of conductive and non-conductive micron particles. Ink-based sensors developed by Tekscan, Inc. [16] consists of two thin, flexible polyester sheets which have electrically conductive electrodes deposited typically in row–column pattern separated down to about 0.5 mm (Fig. 3 taken from [16]). Before assembly, the patented, thin semi-conductive ink is applied as an intermediate layer between the electrical contacts. When the two polyester sheets are placed on top of each other, a grid pattern is formed, creating a sensing location at each intersection.

The conditioning circuits of resistive-based tactile sensors are fairly simple, which is one of their advantages. Fig. 4 shows a 3×3 array of resistive taxels and the circuitry that can be used to implement a tactile transducer.

3. *Capacitive based sensors*. A capacitive taxel is a capacitor whose capacitance changes with the applied force. The force can produce either the change in the distance between capacitor plates or its area.

A good design of a high resolution sensor implies: (a) small dimension taxels; (b) the maximization of the capacitance and the change of its value when force is applied, which advises using high permittivity dielectrics such as polymeric based materials; (c) high sensitivity. Generally speaking, if the capacitor plates area to distance

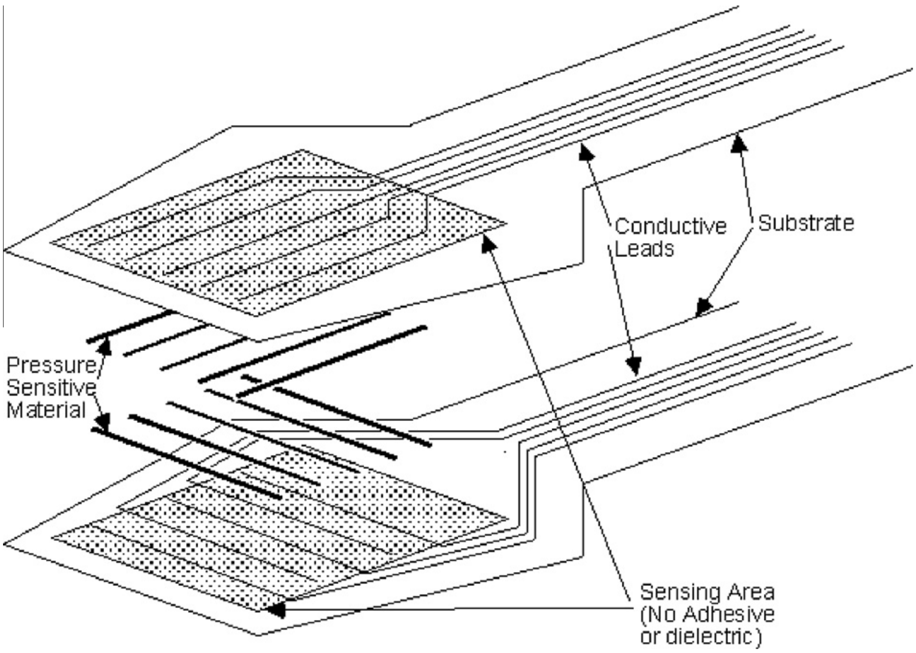

Fig. 3. Tekscan resistive sensor [16].

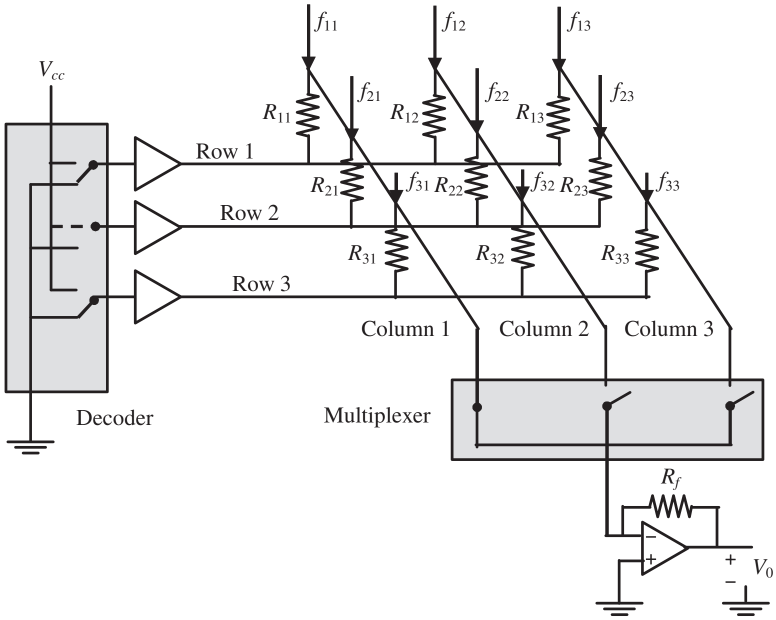

Fig. 4. Resistive tactile transducer.

ratio is smaller than one, the change of plates area is better, which recommends a coaxial cylindrical capacitor (Fig. 5a).

Nevertheless, and even other solutions have been proposed [17], parallel plate capacitors are easier to fabricate than cylindrical ones, which justify their popularity even nowadays (e.g. [18]).

To measure the change in capacitance, several conditioning circuits can be used depending also on the type of the desired output signal. A few examples for a dc output voltage: (a) a current generator that charges the capacitor (taxel) for a fixed time interval, the capacitor voltage being then proportional to the inverse of the capacitance; (b) an oscillator whose running frequency depends on the capacitance value [19] followed by a frequency-to-voltage converter; (c) an AC Wheatstone bridge followed by an instrumentation amplifier and a peak detector. The

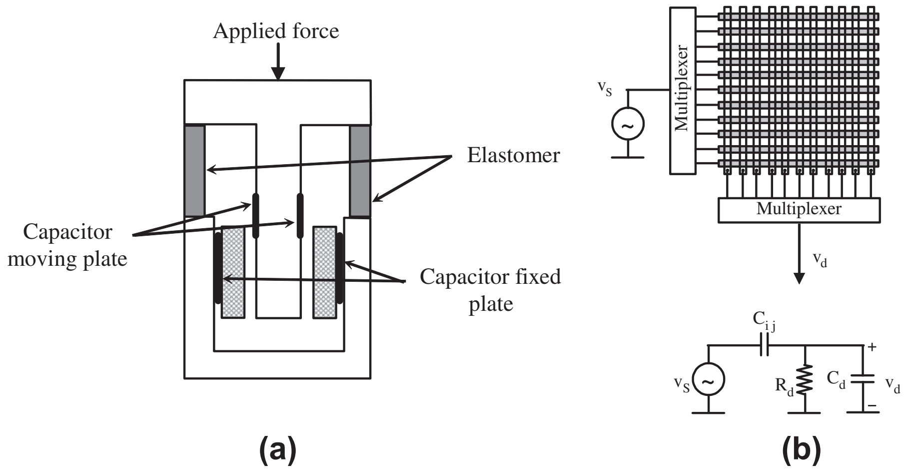

Fig. 5. (a) Capacitive taxel based on a cylindrical capacitor; (b) voltage-based conditioning circuit and its equivalent electric circuit: C_{ij} – taxel (i,j) capacitance; R_d and C_d – equivalent resistance and capacitance of the circuit yielding v_d.

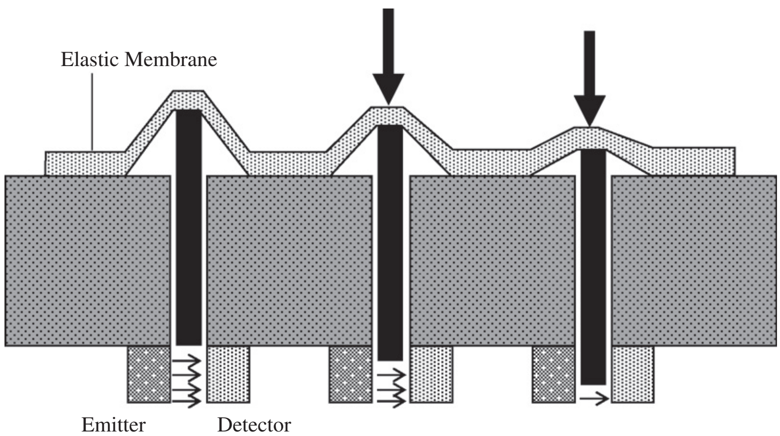

Fig. 6. Optical obstruction-type taxels.

circuit of Fig. 5b yields an ac voltage, v_d whose value depends on the capacitance of each taxel, C_{ij}.

Like other capacitive sensors, tactile ones are prone to capacitive coupled interference namely when they are place close to robot metallic parts (stray capacitances). This means that when quantitative, accurate information is required – which is not the case for instance of tactile sensors for touchpads, good circuit layout and mechanical design of the touch sensor is needed to minimize the problem [20]. Also, careful and dedicated conditioning circuitry

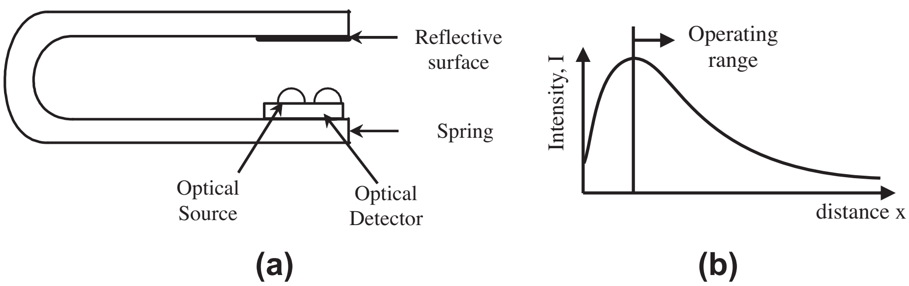

Fig. 7. (a) Left: optical reflective-type taxel; (b) right: light intensity, I, versus distance between the reflective surface and the light emitter–receiver, x.

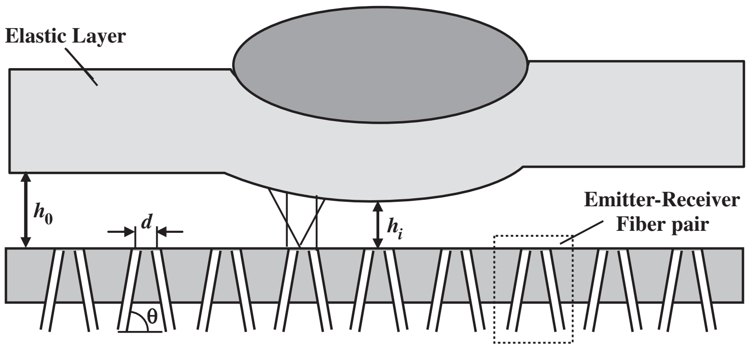

Fig. 8. Optical fiber based reflective-type taxel.

is required to take advantage of the excellent sensitivity and repeatability achieved by some implementations of capacitive sensors [21].

4. *Optical Sensors*. The operating principles of optical-based sensors may be included in one of two types: intrinsic, when the intensity, phase, or polarization of the transmitted light is modulated by the applied force without interrupting the optical path, and extrinsic when the applied force interacts with the light external to the primary light path. In robotic tactile sensing, the extrinsic sensor based on intensity measurement is the most widely used due to its simplicity of construction, signal conditioning and information processing. Two examples of optical transduction based taxels:
   - Modulating the intensity of light by moving an obstruction into the light path. The force sensitivity is determined by a spring or elastomer (Fig. 6).
   - Modulating the intensity of light by moving a reflective surface into the light path (Figs. 7a and 8). The intensity of the received light is a function of distance (Fig. 7b), and hence of the applied force.

Among the positive characteristics of optical sensors for robotic applications are their low susceptibility to electromagnetic interference, intrinsically safety and low electrical wire demand.

5. *Optical fiber based sensors*. Apart from the uses just mentioned where optical fibers are used for light transmission only, an optical fiber can be used as the sensor itself. The underlying idea is the light attenuation in the core of a fiber when a mechanical bend or perturbation (of the order of few microns) is applied to the outer surface of the fiber. The attenuation depends not only on the radius of curvature and spatial wavelength of the bend but also on the fiber parameters. A recent example using also nanoparticles is described in [22].
6. *Piezoelectric sensors*. Some materials, like quartz, ceramics and polymers have piezoelectric properties and can thus be used for tactile sensing. Polymer polyvinylidene fluoride (PVDF) and ceramic lead zirconium titanate (PZT) are perhaps the materials more widely used. The taxel is made by applying a thin layer of metallization to both sides of the piezoelectric material, constituting the whole a parallel plate capacitor (Fig. 9).

The conditioning circuit of a piezoelectric sensor is based on ultra-high input impedance amplifiers and the bandwidth of the circuit does not go down to dc, which means that, as it is well known, piezoelectric transducers are not adequate for static force transduction. This problem can be overcome by vibrating the sensor and detecting the difference in the vibration frequency due to the applied force [23].

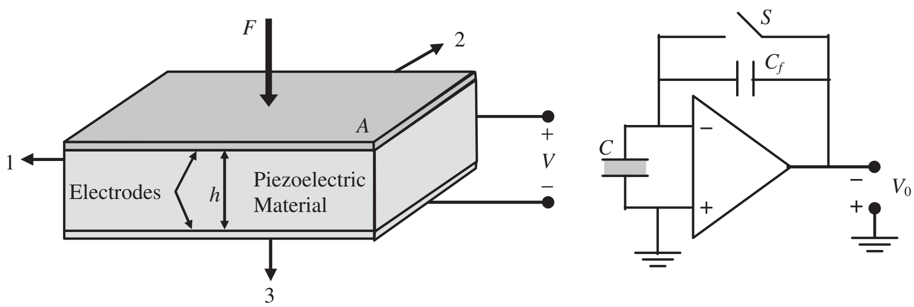

Fig. 9. Piezoelectric based taxel and conditioning circuit.

7. *Magnetic based sensor*. The changes of the magnetic flux density, of the magnetic induction of an inductor or the magnetic coupling between circuits are the most used principles in magnetic tactile sensing. One way of measuring the magnetic flux is using a device whose magnetic properties are force dependent (e.g. magneto-resistance). Using a magnetoelastic material for the core of an inductor its electrical parameters change when force is applied to the core (e.g. [24]). The same type of material used in the core of a transformer leads to magnetic coupling changes between transformer windings under the same conditions, that is, when force is applied to the core.

Magnetorestrictive or magnetoelastic based tactile sensors may have some positive characteristics, namely high sensitivity and physical robustness. Nevertheless, they still fail to be a valuable alternative to the types of tactile sensors above-mentioned.

8. *Deformation based sensors*. The fact that the surface of a material changes in length when it is subjected to external forces can be used for tactile sensing. This deformation is then converted to the electrical domain by means of strain gauges made either from resistive elements or from semiconducting material and bonded to the stressed material. The conditioning circuit more commonly used includes a Wheatstone bridge followed by an amplification stage.

2.3. Tactile sensors: state-of-the-art

In recent years, tactile sensors have been under particular attention due mainly to two domains of applications not exactly related to robotics: (1) human machine interfaces (touch screen displays), namely for communication devices and computers [25–27]. Touch screen technology has been used since 1980–1990s, but it is the last generations of mobile devices that fostered the research in the last 5 years reflected in a large quantity of patents; (2) medicine, namely minimally invasive and remote surgery and therapy and tissue characterization [28–32]. Virtual reality applications are also playing a part on haptic sensing development [33]. Nonetheless, and with the exception of the two-above mentioned cases, the development of tactile and touch sensing has evolved but not in a particularly well oriented way for several reasons. It is true that contrary namely to sight, touch does not produce well quantified signals, which means that a lot of work has been necessary just to deal with the basics of collecting the most relevant data, but perhaps one important reason has to do with the lack of objective and thus of detailed required specifications. Particularly in the domain of tactile sensors, specifications do naturally change with the application but the definition of some general purpose values would clearly provide a sounder base for sensor development. Several authors (e.g. [34–37]) did contribute to the clarification of the major requirements of tactile sensors for robotic applications, but in no decisive way. In the absence of such specifications the development related with touch sensing has been either driven by applications [38–45] or as a product or by-product of micro- or nanotechnologies that use the transduction principles mentioned in Section 2.2, namely silicon or polymer based micro-electro-mechanical-systems (MEMSs) and nanotechnologies.

As in other domains, micro- and nano-technologies are particularly attractive to tactile sensing implementation because they can produce not only high density arrays of sensors but also devices incorporating both the sensors, the required conditioning electronic circuits and even the hardware for signal acquisition, digital signal processing and transmission (embedded devices, smart sensors, i.e., sensors with namely self-diagnostics, calibration and testing capabilities). The devices can and should also incorporate temperature and humidity transducers, quantities that influence the tactile sensing performance, but that are also important by themselves because they convey tactile information.

2.3.1. MEMS tactile sensors

The large majority of tactile sensors recently developed use, more or less intensively MEMS technology. They are mainly either polymer with organic material substrate based or silicon based sensors.

Polymer-based sensors [46–51] usually use piezoresistive rubber as force sensing element. Polymer-based sensors are more suitable for wide area tactile sensors than silicon sensors because of their lower fabrication cost per unit area but have the disadvantages of low spatial resolution (around 2 mm) and upper limitation of the number of taxels due to wiring. The organic-FET switching matrix solution used in [49] is an improvement but long term reliability in this type of application remains to be evidenced and the integration density of organic-FET is much lower than the current silicon technology.

Reports of silicon-MEMS tactile sensors abound in the literature (e.g. [52–57]). Silicon micromachined sensors take advantage of silicon high tensile strength, reduced mechanical hysteresis and low thermal coefficient of expansion. Most of silicon-MEMS tactile sensors are based on piezoresistive or capacitive taxels, and through the integration of a switching matrix fabricated using CMOS technology, the number of wires can be reduced. The CMOS technology allows also the integration of the taxels array conditioning circuits. Silicon micromachining tactile sensors allow higher spatial resolution than polymer-based tactile sensors but it is difficult to realize flexible sensor surface. In [57] a solution to this problem is presented. By their nature, MEMS tactile devices are prone to mechanical damage. To overcome this problem and also to provide a flexible skin like coating over the sensors polydimethylsiloxane (PDMS) can be used. It is a waterproof, chemically inert, and non-toxic silicon-based organic polymer supplied as a two part mix, a monomer and hardener, which are combined at a weight ratio of 10:1, commonly used for embedding or encapsulating electronic components.

2.3.2. Nanotechnology tactile sensors

In the present context, nanotechnologies encompass technologies that work on the nanometer scale independently of their output, material, device or system.

To our knowledge, no fully nanoscience based tactile sensor has yet been produced. There are however reports of tactile sensors using nanomaterials (nanotubes, nanoparticles and nanowires) (e.g. [58–60]), some of them patented protected [61]), and of nanomaterials that can be used for very low force sensing [62] and for touch screens [63,64]. Nevertheless, perhaps the most interesting implementation of a tactile sensor using nanomaterials is reported in [65]. A 100-nm-thick film is built on an electrode-coated glass backing. On top of the glass are five alternating layers of gold and cadmium sulfite nanoparticles, separated from each other by polymer sheets. The device is topped off with an electrode-coated, flexible plastic sheet. When the plastic that covers the sensor is pressed, the nanoparticle layers become closer and an electrical current flows. When electrons bounce between the nanoparticle layers, the cadmium sulfite nanoparticles glow and the light can be picked up on the other side of the glass. Both the sensor's output electrical current and light are proportional to the pressure on the sensor. It was reported that when recording the received light with a camera, the nanofilm can take about 5–10 readings per second, while recording the electrical current can raise those figures to about 20–50.

The sensor is reported as having a resolution of 40 μm horizontally and about 5 μm vertically. When pressed against a textured object, the film creates a topographical map of the surface, by sending out both an electrical signal and a visual signal that can be read with a small camera. The spatial resolution of these "maps" is as good as that achieved by human touch. The sensor is aimed at to improve minimally invasive surgeries but its potential in helping robots grip sensitive objects is very attractive even if the sensor cannot inform on the direction of pressure. It remains to see if nanoparticle layers can sense this kind of tactile information that is required for dexterous manipulation of sensitive objects.

2.4. Tactile sensors applications

Throughout the past paragraphs we have mentioned domains where tactile sensors have been used. We elaborate here about the most common applications.

2.4.1. Touch screens

Although very interesting as man–machine interfacing devices, basic touch screens are quite simple from the point of view of the tactile sensing hardware component but they require a controller with processing capability to run the software that determines the point or points of contact. The best quality touch screen monitors are based on surface acoustic waves (SAWs) sensing [66]. Two transducers (one receiving and one sending) are placed along the two axes (x,y) of the monitor's glass plate (Fig. 10a). Also placed on the glass are reflectors that reflect the electrical signal sent from one transducer to the other (Fig. 10b). When the user touches the glass surface, the user's finger absorbs some of the energy of the acoustic wave and the receiving transducer is able to detect it and can locate it accordingly (Fig. 10c). The screen has no

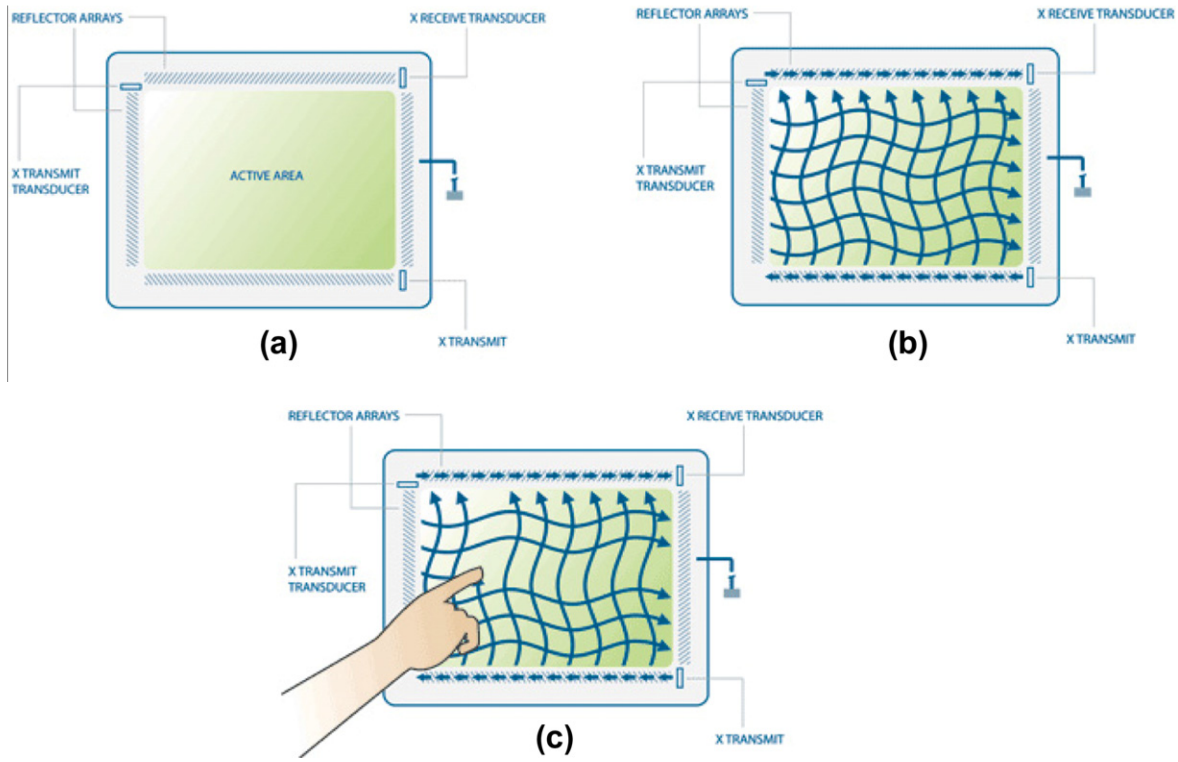

Fig. 10. Surface acoustic wave touch screen. (a) Constitution; (b) non-disturbed acoustic waves pattern; (c) acoustic wave pattern when touched.

metallic layers, allowing for 100% light throughput and thus perfect image clarity, which makes this type of touch screens the best for displaying detailed graphics. Because it is glass constructed, SAW touch screens are durable, can operate even if scratched, and some of their disadvantages, namely the possibility of false touches due to moving liquids or condensation, of creation of non-touch areas due to solid contaminants, and the vulnerability to bad use can be overcome by special design. SAW screen must be stimulated by finger, gloved hand, or soft tip stylus.

SAW touch screens are not efficient for drawing and dragging and do not allow multi-touch detection, i.e., simultaneous detection of touches in different points of the screen. Multi-touch is increasingly necessary when operating smart devices running applications, such as web browsers, requiring using more than one finger (or any object) to stretch, rotate, or shrink an object, and scroll through menus. Capacitive-based sensors using In-Plane Switching (IPS) technology like those used in Apple iPad and in late versions of the iPhone are then a common solution.

2.4.2. Medical devices

Arrays of tactile sensors have been used for breast cancer detection as an alternative to ultrasound based systems, mammography, and other complex systems. An array of 12×16 tactile sensors can be more sensitive than the human sense of touch and the detection of lesions as small as 5 mm under the skin's surface is possible. One example of a capacitive-based palpation imaging system for clinical breast examination is described in [67,68]. The sensing probe has 200 sensors and the system is under exploitation with success [69].

Arrays of tactile sensors of different sizes and configurations have been used also for a wide variety of medical applications, namely: minimal invasive surgery, management of diabetic foot, orthotic assessment, optimization of the seating and positioning of the neurologically compromised people, prosthesis and brace fitting, orthopaedic joint research, and dental prosthesis (e.g., tooth contact and occlusal force balance) [70]. In [71] some of these applications are discussed and framed in the development of tactile sensing.

After non-invasive surgery, minimal invasive surgery (MIS) is the more aimed procedure because of the less negative impact it has on patients and also because it shortens hospital stays, recovery time and often costs. There are several techniques that can be classified and minimally invasive. Most of them are carried out through the skin or through a body cavity or anatomical opening and recur to laparoscopic devices for indirect observation of the surgical field and to remote-control manipulation of instruments. Fig. 11a shows the commercial available robot-assisted da Vinci MIS [72]. It consists of three major components, an input device (surgeon's console), a digital interface (vision system), and an output device (manipulator, patient-side cart). Currently, the basic system does not incorporate tactile or haptic sensing capabilities but several works have been carried out in that direction both for surgery (e.g. [73,74]) and training purposes (e.g. suture training [75]).

Gait analysis can also benefit from tactile sensors use. Fig. 12 shows an in-shoe sensor developed by Tekscan Inc. to provide information regarding the symmetry in foot function during gait. Asymmetry in foot function during gait can generate undesired torque and stress components that, over-time, place wear and tear on body tissues and can potentially cause symptoms of discomfort and pain.

Tactile sensing has been commercially introduced in dental implants. The patented technology [76] included in the Tactile Technologies, Inc., ILS system [77] allows obtaining the mechanical image of the maxillary bone contour without removing any gum tissue. The sensor uses a matrix of micro-needles that are inserted through the gum tissue until contact with bone is attained. The needles used are ultra-thin with specially designed geometry to ensure negligible trauma. Their insertion is measured using miniature position encoders and digital signal processing electronics [78].

2.4.3. Industry

Industrial applications of commercial tactile sensors are particular numerous in the car industry [70]: brake pad de-

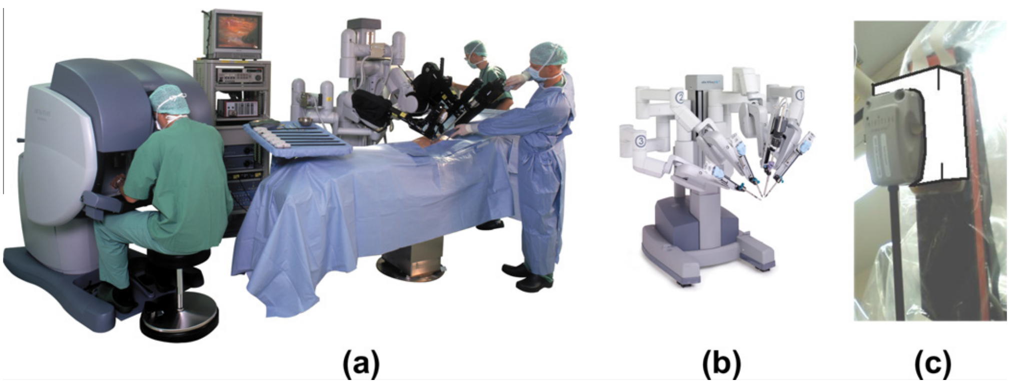

Fig. 11. (a) da Vinci surgical system (Courtesy of Intuitive Surgical, Inc.). From left to right: surgeon console, vision system, and patient-side cart; (b) detail of the patient car; (c) detail of the positioning of a sensing module for tool-tissue force interaction measurement to fit between a da Vinci arm and da Vinci surgical tool [73].

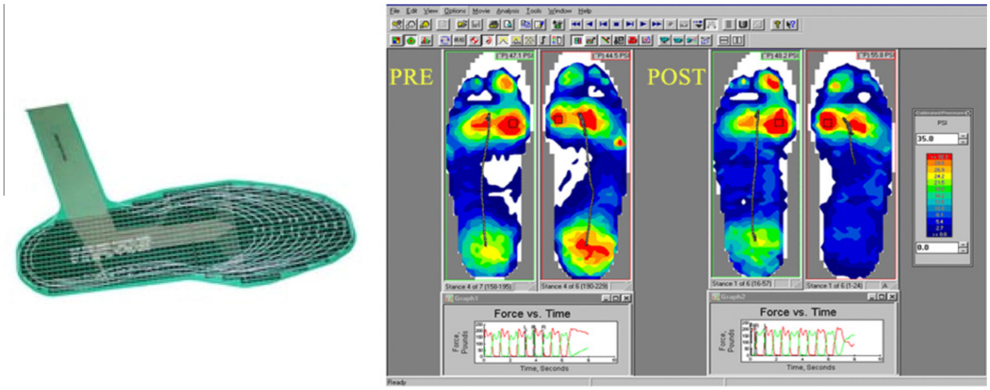

Fig. 12. Pre- and post-orthotic pressure (scale raises from blue to red). Hardware: Tekscan F-Scan system. Number of sensing elements: 960/foot; spatial resolution: 4 sensors/cm^2; size of sensor: trimmable from men's size 14 USA; sampling rate: 165 Hz; pressure range: 1–150 psi; sensor thinness: 0.15 mm (Courtesy of Tekscan Inc.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

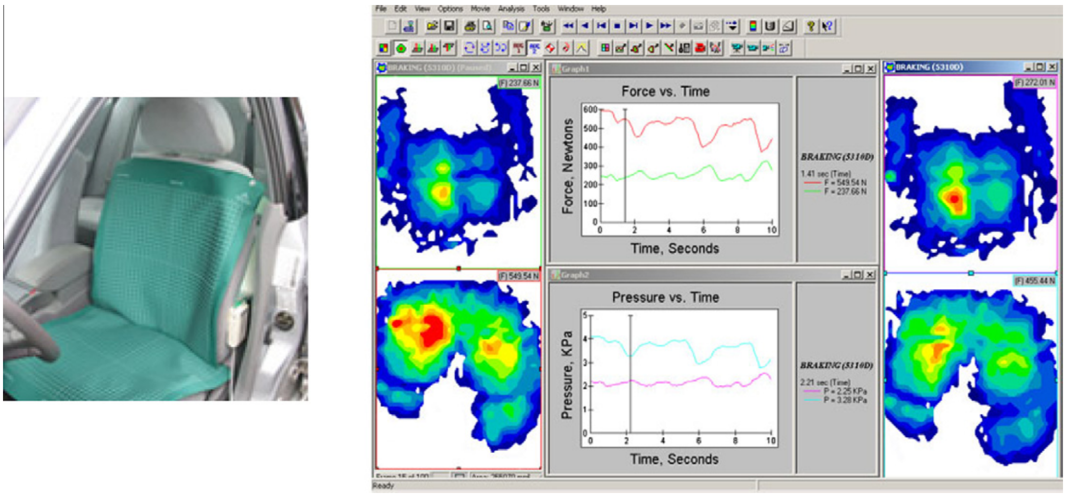

Fig. 13. Left: car seat with Tekscan; Inc. tactile sensors; right: pressure distribution of the driver before and when he prepares to apply the brakes. (Courtesy of Tekscan, Inc.).

sign and performance assessment based on the measurement of the dynamic pressure distribution between brake pads during actual braking; assessment of door mounting quality trough monitoring of pressure distribution in hinges and door latches; assistance in windshield wiper design through analysis of the force distribution between the windshield and the blade at various positions along blade length; tire to wheel interface assessment by measuring the bead seat/seal pressure profile; tire tread design performance evaluation and suspension testing analysis; and design of automotive seats (Fig. 13).

2.4.4. Robots

Scientific and technical literature includes several different tactile sensing implementations for robotic applications, some of which are referred throughout this article. The goal is to provide robot manipulators (hands/fingers) with as accurate information as possible about the objects to grab, hold and handle. How to achieve these and other objectives is detailed in [79] where the authors present a robot tactile sensing classification worth mentioning.

Fig. 14 shows an example using commercial products, a robotic hand from Barrett Technologies, Inc. [80] and tactile sensors from Pressure Profile Systems, Inc. (PPS) [21].

An implementation of tactile sensing in a commercial Willow Garage PR2 robotic platform using capacitive sensors also manufactured by Pressure Profile Systems, Inc. is described in [81]. Each robot gripper fingertip is instrumented with a pressure sensor array consisting of 22 individual cells. The 22 cells are divided between a five by three array on the parallel gripping surface itself, two sensor elements on the end of the fingertip, two elements on each side of the fingertip, and one on the back (see Fig. 15). The sensors measure the perpendicular compressive force applied in each sensed region. The sensing surface is covered by a protective layer of silicone rubber that provides the compliance and friction needed for successful grasping. Equipped with such tactile sensing, PR2 is capable of picking up and setting down delicately, but

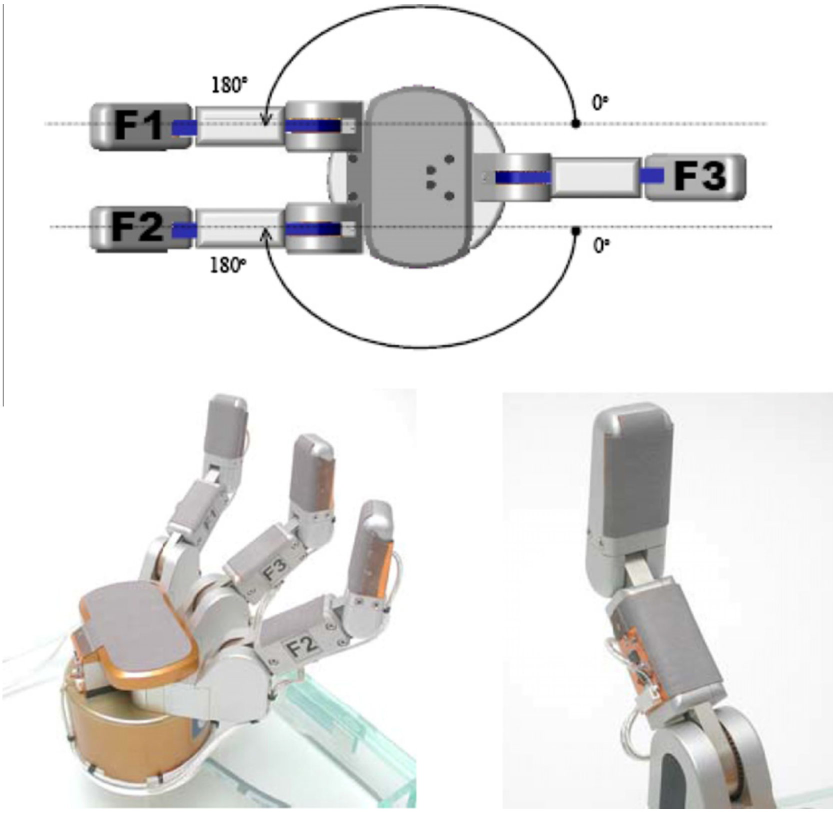

Fig. 14. Barrett hand. Top: basic hand; bottom left: hand with PPS sensors; bottom right: close-up of PPS sensors on the finger. (Courtesy of Barrett Technologies, Inc. and Pressure Profile Systems, Inc.).

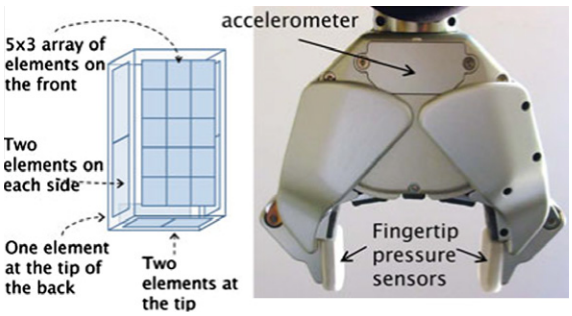

Fig. 15. The PR2 robot gripper. The pressure sensors are attached to the robot's fingertips under the silicone rubber coating [81].

firmly, real-world objects without crushing or dropping them.

Also capacitive pressure sensors [82] have been developed by the Biomimetics & Dextrous Manipulation Laboratory (BDML) of Stanford University, led by Professor Mark Cutkosky namely to improve grasping with an under-actuated hand. Fig. 16 exemplifies the installation of such sensors on a Robotiq Adaptative Gripper [83].

Optical sensors have also been used to convey robot arms tactile and haptic perception. Fig. 17 shows a robot arm equipped with an optical three-axis tactile sensor to improve sensitization quality in robotic hand system

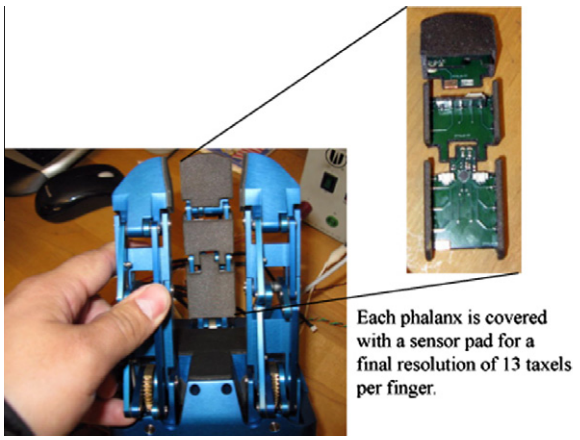

Fig. 16. Stanford University BDML tactile sensors in a Robotiq Adaptative Gripper.

[84]. The tactile information is used as feedback for the arm actuators and is obtained by digital processing image data. The tactile sensor is based on the optical waveguide transduction method [85]. As described by the authors, the sensor consists of an acrylic hemispherical dome, an array of 41 pieces of sensing elements made from silicon rubber, a light source, and an optical fiber scope connected

Fig. 17. Robot arm mounted with optical three-axis tactile sensors.

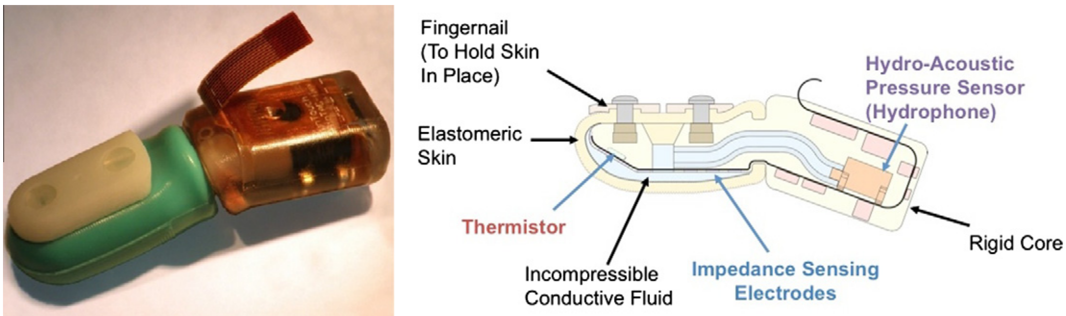

Fig. 18. SynTouch BioTac tactile sensor.

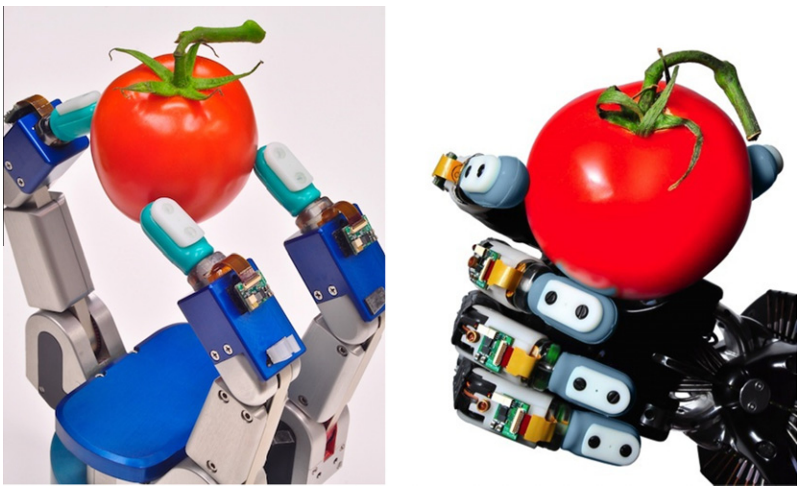

Fig. 19. Barrett hand (left) and Shadow hand (right) with BioTac equipped with SynTouch BioTac tactile sensors.

to a CCD camera. The sensing element has of one columnar feeler and eight conical feelers that remain in contact with the dome surface and optical fibers conduct the light emitted by the light source towards the edge of the dome. When an object contacts the columnar feelers they collapse due the contact pressure and light is diffusely reflected out of the reverse surface of the acrylic surface because the rubber has a higher reflective index. It is the image with bright spots caused by the collapse of the feelers that is processed to provide tactile information.

SynTouch, LLC has been working of tactile sensors aiming at emulating, as close as possible, the fingers sense of touch. The most impressive result is the so-called biomimetic BioTac sensor depicted in Fig. 18, which integrates temperature, force and vibration sensing capabilities using a thermistor, a set of impedance sensing electrodes and a hydrophone, respectively. The current available version of the BioTac sensor, which is an upgrade of the work reported in [14], is well described in [86]. BioTac sensors are available not only as an evaluation kit but also as kits for the Barrett hand and the Shadow hand [87] (Fig. 19). The potential of the BioTac sensor is considerable and claims of achieving better performance than humans for special tasks have already been reported [88].

3. Conclusions

From the previous paragraphs, one can conclude that the basic tactile sensing transduction principles are well established (emphasis on resistive, capacitive, piezoelectric and optical) and that micro- and nanotechnologies provide the means to implement increasingly complex sensors. However, it should be mention here that even if the number of manufacturers producing general purpose or custom tactile sensors is small, they do exist (e.g. Tekscan, Inc. Pressure Profile Systems, Inc., Tactex Controls) some with designs that aim human-like compliance and robustness (e.g. SynTouch LLC). For selection purposes, the specifications of the devices include dimensional parameters (width, length, and thickness), pressure range and allowable over-range, and sensing area and spatial resolution. Additional considerations include flexibility, saturation force, linearity error, drift, repeatability, hysteresis, response time, and operating temperature. In the case of tactile imaging sensors, the type of electrical output may be also an alternative: analog current (4–20 mA), analog voltage, non-modulated or modulated analog voltage, and digital output (e.g. RS232, RS422, and RS485, IEEE 488).

The number of people involved in research and development of tactile and haptic sensing and the number of reported works has increased particularly in the last couple of years but the penetration of tactile sensors in Robotics, particularly in industrial robotics is still extremely low. Why? We think that basically there is no real market-oriented driving force boosting the tactile sensing domain: industrial automation aims efficiency at low cost. This generally means using well established reliable and as simple as possible technologies. Robots with tactile sensing are not at that stage and some applications that could profit from them are implemented by forcing a structured environment and using simpler sensing devices like proximity sensors; other domains like medicine, particularly surgery, and service robotics are starting to play that role only now. To this we must add two other considerations: (1) tactile and particularly haptic sensing is quite demanding not only in terms of hardware but also of software. The extraction of information from tactile sensors may require the implementation of complicated algorithms; (2) the hardware and software available, even at an experimental level are still not adequate for some already defined needs.

Our vision of the future in what tactile sensing is concerned is optimistic but only moderately. Assuming that the industry will not change very much its production style in the near future, we think that it will be up to scientists and engineers to go on developing new sensors suitable for other domains of applications. Robots to operate in unstructured environments will benefit from the incorporation of the functionalities provided by tactile and haptic sensing. Medicine is clearly another example of present and future market for tactile sensors because there is already demand for solutions for instance to help surgeons in minimally invasive surgery.

Like it happened in the past in other domains, we believe that it is up to research to produce sensing devices and systems that later will interest industry. We expect and believe that the technology will be able to overcome some of the current limitations of tactile sensing such as taxel dimension (resolution) and arrangement (array organized sensors suffer from crosstalk, i.e. several taxels can be excited by a very localized force), and integration of all components required to output tactile sensation (sensors, conditioning circuits, processing units, etc.). Nanosciences and nanotechnologies will probably provide answers to these problems but no one can assure if the solutions will have a major impact on Robotics and when they will be available.

It seems relatively undisputable that tactile and haptic sensing finds a favorable ground in applications where robots operate in unstructured environments or equivalently when robots change of working environment. Medical, agricultural, livestock, food, prosthetic, and other niche industries are already demanding and using tactile sensing not always incorporated in a robot [16,89]. The number of robots with dexterous grippers and manipulators requiring tactile and haptic sensing is expected to increase but it is almost impossible to foresee up to what extent.

A subject that has been rarely addressed is wireless tactile sensors. It is clear that whenever the sensors need to be applied for instance on a rotating surface the connecting wires become a major problem. Optical solutions have already been proposed (e.g. [90]) but the alternative of using RF based wireless sensors is increasingly more interesting with the results obtained at the University of California, namely within the framework of Pister's Smart Dust project [91,92], and of other research groups [93]. We believe that robots with tactile and haptic sensing will be able to benefit from all the work that has been developed in the context of embedded wireless distributed systems. In the near future, it is plausible to imagine the production of smart wireless taxels or smart wireless arrays of taxels possibly incorporating other enriching sensing capabilities, such as temperature.

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