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Robots with a sense of touch

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Tactile sensors provide robots with the ability to interact with humans and the environment with great accuracy, yet technical challenges remain for electronic skin systems to reach human-level performance.

The development of the sense of touch in robotics is an engineering challenge. The so-called "electronic skin", which covers different parts of a robot with sensors responding to mechanical and other environmental stimuli, requires system-level development that spans from materials and electronics up to communication and processing. Robots equipped with tactile sensing may have many different applications ranging from industry to health care, each dictating specific requirements and tradeoffs in terms of the range of operating forces, frequencies, and resolution. In general, large deformations in the sensor's material allow measuring external forces with greater accuracy. Such elements should be reliable and robust, as they usually protect the electronics against impacts and scratches, as well as dust and water. High sensitivity has to be in balance with durability, which is key for any artificial device used daily in domestic or industrial scenarios. In addition, the response of the sensor should not change with time nor with temperature, and have close to zero hysteresis. In this commentary, we focus on skin systems for robotics, discussing their key requirements and related issues.

Why robots need an electronic skin

Even though autonomous robots mainly rely on some form of visual perception to interact with the surrounding environment, there are tasks that would be impossible or too complicated without the sense of touch. Inferring contact information from vision requires complex 3D scene reconstruction, which limits the effective deployment of robots in dynamical environments. Tactile feedback has the potential to improve robot interaction skills. For example, in the control of object grasping and manipulation, touch provides important information related to the position of the object in the hand informing the controller about the object local surface curvature, friction, or the force exerted by the fingers. Overall, touch helps the robot to deal with uncertainties – about the object position or its shape – that make purely vision-based approaches difficult in unstructured environments.

Active control strategies rely on contact information to explore and localize objects with great accuracy[1, 2]. Recent research targets algorithms that learn control strategies to maintain a stable grip in the presence of uncertainties or perturbations[3]. In particular, slip detection and force control allow manipulating fragile objects or those with slippery surfaces. These tasks require tactile sensors to provide accurate estimation of normal, tangential forces as well as incipient slip from tiny vibrations. Tactile sensing can also reveal objects properties that are hidden (or difficult to extract) using vision. Solving this task requires being able to meaningfully explore objects[4] and, through machine-learning algorithms, build a coherent representation that merges information extracted at different spatial locations as obtained from several contact points[5].

Besides manipulation, complex robots — as for example humanoids — perform tasks that involve making and breaking contact with the environment through any part of the body. Contacts can happen either accidentally or because the robot searches for support in dynamic movements. In this case, the sensors need to be robust enough to cope with unpredictable multiple contacts. Combined with force/torque sensing technologies, tactile sensing allows robots to detect contacts, estimate interaction forces and regulate them for simultaneous whole-body postural and compliance control[6].

The ability of detecting touch on the entire body of the robot supports natural human-robot interaction involving physical contacts that greatly enhance the potential application of robots in environments requiring not only safe, but also gentle tender contact with humans, such as in nursing or elderly care.

Conventionally, teaching specific tasks from demonstration relies on feedback obtained from localized force/torque sensors[7]; wide-area electronic skin technology can significantly enhance such feedback information (figure 1a and 1b). A wearable suit with distributed tactile (figure 1c-e), inertial and force/torque sensing[8] can provide the necessary information about the human interactant. Combined with data extracted from other non-wearable sensing systems (for instance, motion capture and force plates), this information allows performing the inverse dynamics computations used to understand the dynamics of physical interaction[9].

Requirements

Human touch is often the reference system for robotics in terms of resolution, frequency range, sensitivity and other parameters. Inspirational is also sensory fusion, which is the combination of proprioception and inertial sensing (that form the body state configuration) with tactile sensing (localized in the skin). The human skin hosts four types of mechanical receptors with different responses that convey rich sensation of mechanical stimulation[10, 11]. Each receptor type has different physical properties — size, localization, shape, structure and materials — that mediate its response to vibrations and steady pressure. It is difficult to find a single tactile sensor that covers all possible input frequencies, spatial resolution and properties of interaction; rather, electronic skin solutions should comprise different sensing elements with diverse properties, implemented through different transduction mechanisms and materials. Although current research focuses on pressure sensing, it is crucial to investigate the development of novel materials and structures that can make sensors respond to external stimuli more accurately, generating signals related to shear, lateral deformation and vibrations — which are fundamental cues to explore and handle objects (controlled slip, finger sliding, re-grasp).

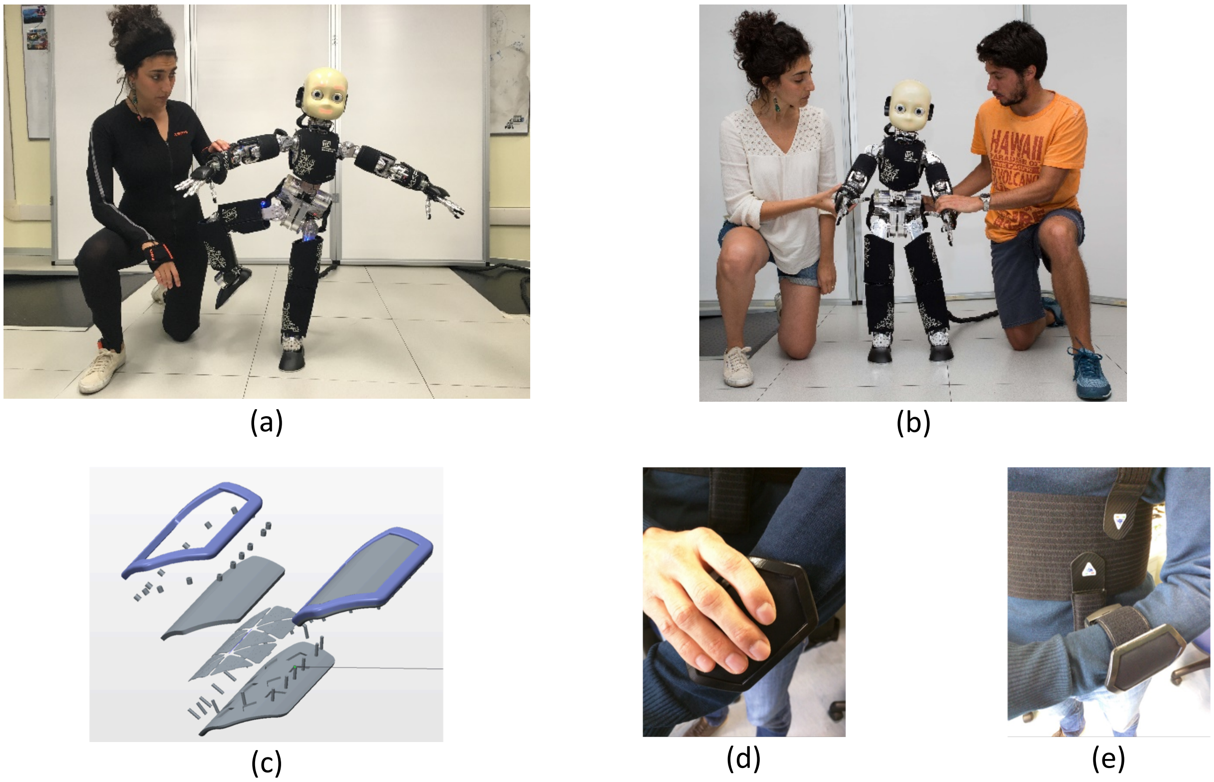


Figure 1: *Examples of whole-body control tasks and human-robot interaction. (a) and (b), balancing tasks under external perturbations; the skin is used together with force/torque sensors and inertial measurements to estimate external forces and compensate them. (c) layout of a wearable device that uses electronic skin to measure body movement and contacts: starting from the bottom layer: plastic support (typically acrylonitrile butadiene styrene), flexible PCB, soft dielectric layer (typically neoprene), protection and final closure; (d) and (e) show the actual sensing components (though limited to a specific body part).*

Humans need to distinguish light touch with high precision for fine manipulation and grasp, and simultaneously sense high pressure for safety, contact detection and localization. Different mechanoreceptors have different sensitivity thresholds, ranging from a skin indentation of 1µm up to 1mm. A soft touch is in the order of 0.3N to 1N, corresponding to 10g/cm^2, whereas a push or a slap correspond to more than 10N (1kg/cm^2)[12]. In practical applications, robustness would require at least an order of magnitude larger breakdown forces. The required frequency sensitivity ranges from few Hz up to few kHz (for texture discrimination and incipient slip of objects during manipulation). The human sensory system can compensate for the intrinsic hysteretic response of skin and for complex deformations (for example due to the non-rigid substrate of the sensors). However, in robotic applications it is preferable to use sensors with reduced hysteresis to avoid complex signal processing. The receptors' spatial resolution depends on their position in the body: on human fingertips it is about 1 mm; on the palm, it decreases by a factor of 10, and on large areas, it can decrease further to 40-50 mm. In order to mimic such spatial density, a fully covered robot needs thousands of skin sensing elements, and this requires minimizing power consumption and wiring, calling for smart sensors readout and bespoke data-communication strategies. Durable and flexible wiring in particular is crucial to connect sensors across movable joints.

In addition, the electronic skin should cover large and non-planar surfaces, as well as recondite details of the fingers and joints, with different shape and curvatures, requiring different degrees of conformability. Some of these parts move, additionally requiring the development of flexible and stretchable components (comprising sensors, electronics and wiring). The compensation of temperature drift is crucial, because the proximity of motors and other electronic devices create temperature gradients across the surface of the robot (from environment temperature up to 80-100°C) that change within minutes. This proximity also entails the development of sensors, electronics, and communication channels robust to electric and magnetic noise (as reported for example in the CE certification directive 2004/108/EC[13]).

Most sensors found in the literature have some of the key requirements listed above, but the majority has drawbacks that hindered their use in robotics, often because they are too rigid or fragile to conform to curved surfaces. Robustness is typically an issue. Finally, in many cases they need complex manufacturing resulting in high cost.

The requirements derived from the human sense of touch are effective guidelines for the development of robots that perform human-like tasks; however, specifications differ in other applications. Whole-body touch might be less fundamental for robots operating remotely (for example in disaster recovery); sensitivity requirements will change considerably in industrial environments where the focus is on heavy loads. Conventional robotic systems operate on feedback loops: performance heavily depends on latency and therefore, differently from human touch, a fundamental parameter is the sensor's readout rate.

Artificial touch sensors

In robotics, the most adopted sensing modes are capacitive, resistive, piezoelectric, optical and magnetic. We describe here their main features and drawbacks highlighting for each system a possible development path to maturity (we make no direct comparison across the performance of the different technologies).

Capacitive sensors consist of two conductive layers separated by a deformable dielectric material. Applied pressure causes the deformation of the dielectric, which in turn changes the capacitance of the structure. The measurement of capacity yields an estimate of pressure. The compatibility of these sensors with flexible substrates and the availability of off-the-shelf components for the readout electronics makes capacitive technology suitable for robotics, especially for large areas[14]. Capacitive sensors are compact, highly sensitive and with theoretically unlimited operational bandwidth (in practical cases the choice of the dielectric material often limits the bandwidth to relatively low frequency ranges). The main drawbacks are the degradation of the elastomeric materials used as deformable dielectric due to mechanical wear and tear, hysteresis, drift of sensitivity due to temperature, and – depending on the materials – relatively complex production processes. Recently, capacitive sensors have been coupled with dielectric materials made of a thin layer of 3D fabric glued to conductive and protective layers[15]. This process greatly improves mechanical figures and durability, sensibly reducing hysteresis. Fabrication is simpler and more affordable for large-scale production, also leading to more reproducible responses.

In *resistive* sensors, two electrodes measure the variation of resistance due to forces applied to the sensor; their design is relatively simple and can be implemented on flexible printed circuit boards (PCB). The readout electronics requires a voltage divider and an off-the-shelf analog-to-digital converter, which are compact and simple. Other advantages are their low cost, low noise and good sensitivity. The main drawbacks are power consumption, hysteresis and the short life of the materials.

Optical sensors emit infrared light and sense when the proximity of an obstacle interrupts the light flux, detecting approaching objects as well as actual contacts. The advantage of proximity sensors lays mainly in safety, as they allow preventing contact altogether. The main drawbacks are the decrease in performance under strong light conditions and power consumption. Solutions based on multiple layers of optical media respond to light diffusion inside the layers due to their deformation, yielding a measure of local pressure[16].

Piezoelectric materials generate charges proportionally to the force applied to the sensor; their response is fast and linear over a large range of stimuli, making them suitable for dynamic force sensing. Polymeric materials, such as polyvinylidene difluoride, are flexible and have long-lasting chemical stability. They have been used for the implementation of tactile sensors based on an integrated device, the POSFET (piezoelectric oxide semiconductor field effect transistor, ref.[17]), where the piezoelectric material, deposited over the gate of a CMOS transistor, senses the force-generated charges. The POSFET allows integration of the readout circuitry with the sensing material minimizing noise and wiring, and maximizing resolution, but requires the development of flexible integrated circuits and a specific post-processing for the deposition and polarization of the polymer over the sensing elements array.

Magnetic sensors[18] embed magnets in a deformable substrate, measuring changes in the magnetic field induced by the relative movement of the magnets due to pressure. The interaction of the magnetic field with metallic objects alters the detected signal and therefore this technology has limited use in robotics.

***Table 1**: types of sensors used in robotics and their main parameters (references in text).*

Sensing mode	Frequency range (Hz)	Minimum detectable pressure	Maximum Force	Spatial resolution	References
Capacitive	0 – 250	2-3 kPa (3-4 kPa)	180 kPa (50 kPa)	5 mm (3 mm)	iCub skin[15] (in brackets, values referring to iCub fingertip)
Resistive	1000	0.1 N	30 N	2 mm	BioTac[19]
Resistive	1000	0.3 kPa	1000 kPa	5 mm	ShadowHand[20]
Optical	0 – 250	1-200 mm (distance range measured)	No force applied	4x4x0.8 mm (size of the single sensor)	CellulARskin[21]

Existing implementations in robotics

Despite the complexity of the development of functional and robust electronic skin, some excellent results have been accomplished addressing the requirements listed above and can be regarded as starting points for the ultimate skin technology. Table 1 summarizes their key technological features; for a thorough review of the most recent tactile sensor technologies, independently from their readiness level for robotic integration, see ref.[22].

In all implementations, including those reported in early works on electronic skin for robotics[23, 24], key features include modularity, flexibility and interconnections with the sensing modes described in table 1. Modularity helps fabrication and cost; in fact, although it is often possible to customize the skin shape to the specific robot, the cost may increase rapidly even for established technologies. For reasons of conformability, most skin systems in the literature involve the use of circuits on flexible PCBs. To optimize interconnections, often sensors form a mesh network with hierarchies that progressively encode information, thus reducing the number of wires. In the following, we report on technologies – also shown in figure 2 – that proved reliable across different implementations on a number of robots.

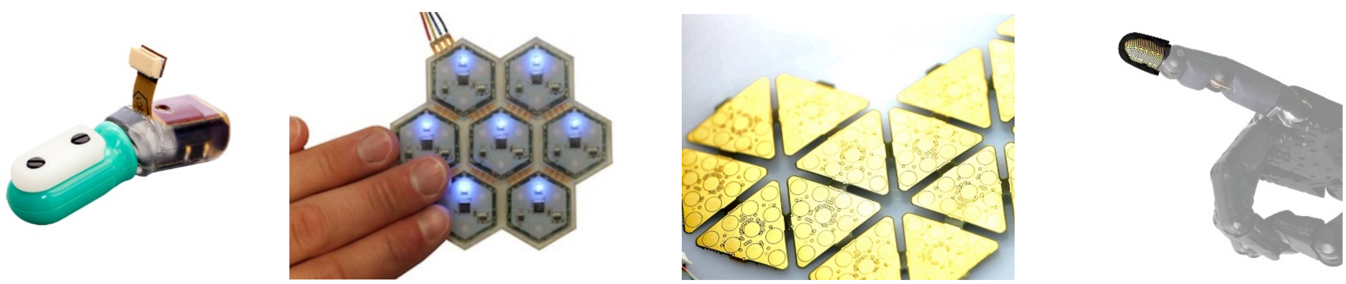
Syntouch[19] is a bioinspired multimodal fingertip with impedance sensors for measuring deformations in response to normal or shear forces, pressure transducers for measuring vibrations and pressure when sliding over textured surfaces, and temperature sensors. The sensing principle is resistive with elastomers covering a fluidic structure. This arrangement propagates the force signal to a remote position, protecting the fragile transducers from environmental damages. The sensor spacing is lower than 2mm and the response to forces ranges from 0.1 N to 30 N. The main limitation is that they are expensive and cannot cover large areas. The activation of the sensing elements in response to pressure is complex as there is no simple relation between the applied local pressure and the response of the sensor. This notwithstanding, Syntouch has been successfully mounted on various robotic hands (http://www.syntouchllc.com/), and it has been used with machine learning techniques in several tasks (discrimination of objects[5], control of slip[25], in-hand manipulation[26]).

Ref.[27] proposes an electronic skin based on hexagonal PCB modules, each hosting three different types of sensors. Each module performs local pre-processing with redundant connections to a mesh network structure. The elements, embedded into an elastomer, can conform to curved surfaces and therefore allow covering large areas of the robot's body[27]. The elastomeric layer also protects the sensors and controls the sensitivity of the underlying transducers. The advantage of this technology is that it offers a solution to cover large areas with multiple modalities, such as temperature, vibrations and acceleration (3D accelerometer), light touch and proximity (optical). Proximity sensors work efficiently for collision avoidance, whereas the accelerometers are used for collision detection[27]. The integration of the data acquired from the accelerometers and the tactile units has been used for robot self-calibration[28].

Ref.[15] reports an alternative flexible capacitive skin to cover both large and small areas of a robot's body, including fingertips. The basic unit is a triangular flexible PCB hosting twelve capacitors and an off-the-shelf capacitance-to-digital converter. One of the capacitors acts as reference to compensate temperature drifts. Up to sixteen patches serially communicate with a microcontroller, which routes the acquired signals to a Controller Area Network serial line, drastically reducing the problem of connectivity for large areas. The dielectric and top layer of the capacitors are also soft and flexible. Tests with different materials are used to fine-tune the sensitivity, hysteresis, and durability of the skin as a function of the application desiderata[15]. A number of robots employ this solution in different ways — for example, for safe interaction with withdrawal reflexes, in human-robot interaction under physical contact, for manipulation, in learning-by-demonstration sessions. Since the response of the sensor is analog, integrating responses from neighboring sensors enables stimuli localization with resolution higher than the sensor spacing (super-resolution[2]).

Ref.[29] describes the use of Laser-Direct-Structuring to fabricate electrically conducting 3D structures that implement fingertips with resistive sensing modes. The readout electronics is very simple and compact, integrated on the same PCB that hosts the electrodes. With off-the-shelf components, the sensing elements can be sampled up to a frequency of 1 kHz. The resulting fingertip, with a resolution of about 5.5 mm, has been integrated on the Shadow Hand[20]. It can sense forces up to 80 N, with a tradeoff between sensitivity and maximum measurable load. Its main drawbacks are hysteresis and the five-step fabrication process that could be an issue for manufacturability. Experiments with these devices involved manipulation tasks such as opening and closing jars and folding paper, which have proven extremely challenging to accomplish without tactile feedback.

In summary, fully integrated robotic skins employ relatively well-established technologies. Due to rapid progress in the field, new sensors are already available that improve resolution and sensitivity[10]. It is high time to bridge the gap between proof of concept and complete electronic skin realizations in robotics by combining materials, high-resolution and sensitivity sensors with an integrated system view typical of robotics engineering, tackling challenges that will create novel opportunities. Integration would benefit from contribution of material science for embedding electronics and transduction in stretchable and conformable materials with increased system-wide robustness.



(a) (b) (c) (d)

Figure 2: *4 examples of technologies for robotic skin systems: (a) the Syntouch fingertip[19]; (b) multimodal hexagonal modules[21]; (c) capacitive triangular patches[15]; and (d) resistive fingertip[29].*

Challenges and opportunities

Although we focused on the analysis of skin technology in the context of advanced robotics, skin is also important in prosthetics[30, 31]. The design of novel limb and hand prostheses aims at a natural replacement of lost functionality; hence, besides the necessary control of the actions of the device, it is crucial to convey natural sensorial feedback. Integrating the sense of touch (and proprioception) enables the perception of the prosthesis as a part of the own body, increasing confidence and dexterity, and decreasing the need for constant visual feedback and cognitive effort in control. Prostheses without tactile feedback are typically used for power grasp and holding, whereas those equipped with haptic feedback enable fine and precise actions — such as pulling the stem from a cherry — that require the evaluation of the shape and consistency of an object (thus its identification), planning the correct grasping and controlling the grip force[30].

Similarly, tactile feedback is crucial for enhancing operability and performance of tele-operated devices, such as robots that replace humans in hazardous environments, or surgical robots where perception of tissue consistency and compliance may improve the precision of the surgeon.

It is clear that the development of electronic skin has reached a state of maturity that enables its use in various robotics applications. A number of robotic platforms exploit the advantage of tactile sensing. To reach human-level performance, however, improvements along several directions are required. Big challenges are the integration of different technologies with complementary transduction properties and the design of novel materials to improve protection. Furthermore, optimization of surface texture can lead to enhanced sensitivity — such as the rims of fingerprints enhance perception of vibrations. Technology advances in materials science can result in stretchable yet robust embedded electronics and wiring.

Beyond these materials and single-device challenges, a major concern in the implementation of fully covered robots is the number of sensing elements and the corresponding wiring, power and communication overhead. Informatics and electronic engineering can help tackling this network-scale problem, by developing data encoding that compresses information and sensors that, similar to their biological counterparts, only send information when and where there is contact, limiting the transmission and processing of data from inactive elements. Neuromorphic event-driven sensing is a possible avenue of research and development to solve these problems[32].

The interested reader may find additional details on the issues involved in complete electronic skin systems — including transduction, signal processing, properties and applications — in ref[33].

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