Tactile Sensing—From Humans to Humanoids

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***Abstract*—Starting from human "sense of touch," this paper reviews the state of tactile sensing in humanoid robotics. The physiology, coding, and transferring tactile data and perceptual importance of the "sense of touch" in humans are discussed. Following this, a number of design hints derived for robotic tactile sensing are presented. Various technologies and transduction methods used to improve the touch sense capability of robots are presented. Tactile sensing, focused to fingertips and hands until past decade or so, has now been extended to whole body, even though many issues remain open. Trend and methods to develop tactile sensing arrays for various body sites are presented. Finally, various system issues that keep tactile sensing away from widespread utility are discussed.**

***Index Terms*—Cutaneous sensing, extrinsic sensing, humanoid robots, robotic skin, tactile sensing, touch sensing system.**

I. Introduction

ROBOTIC devices, limited to the structured environment of manufacturing plants until few years ago, are slowly entering into human life in one form or another. This has led to emergence of interaction and learning issues—more so for humanoid robots. Humanoid robots, introduced as "mechanical knight" by Leonardo da Vinci in 1495 A.D. [1], will eventually work along humans if they understand human intelligence, reason, and act like humans. Since they are expected to simulate the human structure and behavior, they are more complex than other kinds of robots. For example, unlike industrial robots, a humanoid robot is expected to reach its goal while adapting to the changes in its environment—which requires autonomous learning and safe interaction, among many other things. Thus, it is important to study the ways and means of humanoid robot's interaction with the environment.

What happens if we have all sensing modalities other than "sense of touch"? A simple experiment of exploring the objects after putting our hands on an ice block for a while can answer this question. One such experiment, performed by anesthetizing the skin on the hands of a group of volunteers, demonstrates the difficulty of maintaining a stable grasp of objects [2]. The movements become inaccurate and unstable when the "sense of touch" is lost. In another, rather unusual, experiment performed on astronauts at the International Space Station, the vibrotactile cues provided via "sense of touch" are found to be highly indicative of the direction and spatial disorientation [3]. "Sense of touch" allows assessing object properties, e.g., size, shape texture, temperature, etc. It is needed to detect slip, to roll an object between the fingers without dropping it, to develop awareness of the body, and, hence, to differentiate "me" from "not me." Thus, absence of the "sense of touch" (for that matter, any sensing modality) would widen the gap between what is sensed and what is perceived.

As in humans, touch sensing in humanoid robots would help in understanding the interaction behaviors of a real-world object, which depend on its weight and stiffness, on how its surface feels when touched, how it deforms on contact, and how it moves when pushed. Even though "sense of touch" is important, most humanoid projects have not paid any major attention to it *vis-a-vis* other sensory modalities—thereby strongly limiting their interaction and cognitive capabilities. This could partly be attributed to the complex and distributed nature of "sense of touch" and partly to the absence of satisfactory tactile sensors or "taxels" that can be incorporated in humanoid robots. Over the past two decades or so, the pursuit to improve tactile sense capability of robots has resulted in many touch sensors, exploring nearly all modes of transduction [4]–[35]. However, something like a tactile analogous a complementary metal-oxide-semiconductor (CMOS) optical array is yet to come. Production of tactile sensors with innovative designs still continues, but they largely remain unsatisfactory for robotics either because they are too big to be used without sacrificing dexterity or because they are slow, fragile, lack elasticity, lack mechanical flexibility, and lack robustness, and, in some cases, because of their digital nature, i.e., all or none. Some other reasons for neglecting tactile sensing in a general mechatronic systems are discussed in [36].

Design of a meaningful robotic tactile sensing system must be guided by a broad, but integrated, knowledge of how tactile information is encoded and transmitted at various stages of interaction. In this context, the studies on human "sense of touch" can be a good starting point. For centuries, biological systems have inspired engineers [37] and are now inspiring roboticists as well [38]–[40]. Starting from a human "sense of touch," this paper presents the role, importance, and current state of tactile sensing in robotics. This paper is organized as follows: Various terms associated with "sense of touch" are defined in Section II. Following a brief discussion on the physiology of human "sense of touch," its role and perceptual importance are presented in Section III. Using these studies, various design hints for robotic tactile sensing are also presented in Section III. Various

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technologies developed to improve the touch-sensing capability of robots are presented in Section IV. Current trends and methods for the development of tactile sensing arrays, for various body parts, are discussed in Section V. Various issues needed to be considered for the effective utility of tactile sensing in robotics have been highlighted in Section VI. Various open issues related to robotic tactile sensing are presented at appropriate places through out the text and are summarized in Section VII.

II. Sense of Touch—Definitions and Classification

"Sense of touch" is used as a layman's term in the previous section, and before proceeding further, it is imperative to define various terms associated with it. The "sense of touch" in humans comprises two main submodalities, i.e., "cutaneous" and "kinesthetic," characterized on the basis of the site of sensory inputs. The cutaneous sense receives sensory inputs from the receptors embedded in the skin, and the kinesthetic sense receives sensory inputs from the receptors within muscles, tendons, and joints [41], [42]. It should be noted that sensory inputs are not only mechanical stimulations but also heat, cooling, and various stimuli that produce pain.

In context with the submodalities mentioned earlier, most researchers have distinguished among three sensory systems—cutaneous, kinesthetic, and haptic. According to Loomis and Lederman [41] and Klatzky and Lederman [43], a cutaneous system involves physical contact with the stimuli and provides awareness of the stimulation of the outer surface of body by means of receptors in the skin and associated somatosensory area of central nervous system (CNS). The kinesthetic system provides information about the static and dynamic body postures (relative positioning of the head, torso, limbs, and end effectors) on the basis of 1) afferent information originating from the muscles, joints, and skin; and 2) Efference copy, which is the correlate of muscle efference available to the higher brain. The involvement of afferent information from skin in kinesthetic sensing also indicates its dependence on cutaneous sensing. The haptic system uses significant information about objects and events both from cutaneous and kinesthetic systems [41], [43].

On the basis of sensory systems discussed earlier, the perception of a stimulus can be categorized as cutaneous, kinesthetic, and haptic perception. According to Loomis and Lederman [41], the "tactile" perception refers to the perception mediated solely by variations in cutaneous stimulation. Kinesthetic perception is mediated exclusively, or nearly so, by the variations in kinesthetic stimulation. Interestingly, humanoids outperform humans in kinesthetic perception [44]. All perceptions mediated by cutaneous and/or kinesthetic sensibility are referred to as tactual perception. The properties of peripheral nervous system are investigated either with a moving object touching an observer or by the purposive exploration of objects by the observer. Accordingly, the "sense of touch" is classified as passive and active. Loomis and Lederman [41] made a distinction between passive and active touch by adding the motor control inputs to the afferent information, as shown in Fig. 1. In an everyday context, the touch is active as the sensory apparatus is present on the body structures that produce movements.

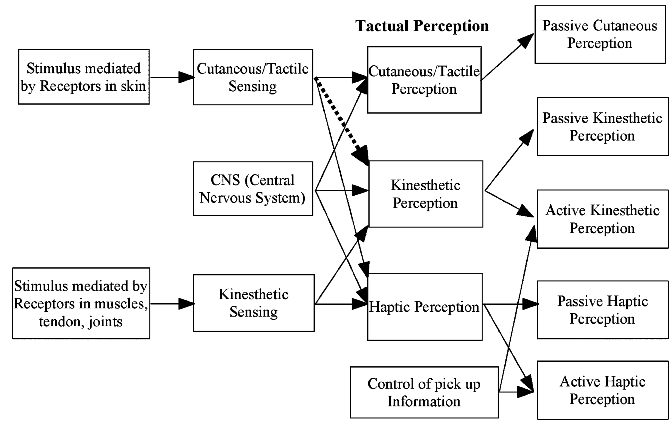

Fig. 1. Components of tactual perception [41]. Dotted line represents the partial dependence of kinesthetic perception on stimulus mediated by receptors in the skin.

Using various terms associated with the human "sense of touch," a parallel can be drawn for robotic tactile sensing. Generally, robotic tactile sensing is related to the measurement of forces in a predetermined area. Jayawant [45] defined it as the continuous detection of forces in an array. Crowder [46] defined it as the detection and measurement of perpendicular forces in a predetermined area and subsequent interpretation of the spatial information. However, this definition is narrow for not including contact parameters other than perpendicular forces and broad for including the "interpretation" of spatial information, which is basically perception and, hence, includes the role of both cutaneous sensing and the corresponding area of analysis in somatosensory cortex of CNS. In this context, the definition of a tactile sensor—a device or system that can measure a given property of an object through contact in the world—by Lee and Nicholls [13] is more appropriate. Studies on cutaneous sensing show that receptors are not just transducers. Both individually and collectively they locally process the stimulus [47]–[49]. Thus, tactile sensing can be defined as detection and measurement of contact parameters in a predetermined contact area and subsequent preprocessing of the signals at the taxel level, i.e., before sending tactile data to higher levels for perceptual interpretation. On similar lines, touch sensing can be termed as tactile sensing at single contact point.

Robotic tactile sensing is broadly classified in Fig. 2. Based on the tasks to be accomplished, robotic tactile sensing is categorized in two ways—"perception for action" (as in grasp control, dexterous manipulation, etc.) and "action for perception" (as in object recognition, modeling, exploration, etc.). In addition to these, "haptics" (not shown in Fig. 2) could be the third category. Haptics involves both action and reaction, i.e., two-way transfer of touch information. Based on the body site, where tactile sensors are located, robotic tactile sensing can be categorized as intrinsic and extrinsic tactile sensing. Intrinsic sensors, which are placed within the mechanical structure of the robot, derive the contact information like magnitude of force using force sensors. Extrinsic sensors or arrays that are mounted at or near the contact interface deal with tactile data from localized regions. Extrinsic and intrinsic tactile sensing are analogous to cutaneous

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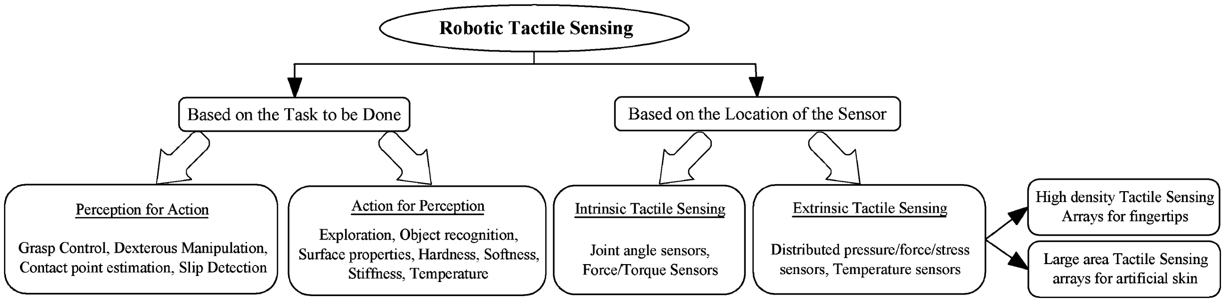

Fig. 2. Classification of robotic tactile sensing.

and kinesthetic sensing, respectively. Like a cutaneous system (see Fig. 1), extrinsic tactile sensing and the computational unit of robots can be termed as an extrinsic tactile sensing system. Similarly, an intrinsic tactile sensing system and haptic system can also be defined.

The extrinsic tactile sensing is further categorized in two ways—first, for highly sensitive parts (e.g., fingertips), and second, for less sensitive parts (e.g., palm). Whereas former requires tactile sensing arrays with high density and spatiotemporal response (∼1-mm spatial resolution and response time of the order of few milliseconds), such constraints can be relaxed for the latter. Both extrinsic and intrinsic tactile sensing can be further classified (not shown in Fig. 2) on the basis of the working principle and the physical nature of the sensors. The working principle of tactile sensors can be resistive, capacitive, inductive, optical, magnetic, piezoelectric, ultrasonic, magnetoelectric, etc. Similarly, the physical nature of the sensors can be flexible, compliant, stiff and rigid, etc. These classifications are discussed in detail in the following section. This paper is primarily focused on extrinsic tactile sensing, and hereafter, it is simply termed as tactile sensing.

III. Human Tactile Sensing—A Basis for Robotic Tactile Sensing

Scientific studies like hand movements for optimum exploration, object recognition, active and passive perception, selective attention, sensory guided motor control, etc., have addressed many issues that are challenging to roboticists as well. In the absence of any rigorous robotic tactile-sensing theory, such studies may be helpful in specifying important parameters like sensor density, resolution, location, bandwidth, etc. They may also bring up new ideas of raising the level of tactile sensitivity and acuity of robots to the human range. Following a brief discussion on cutaneous/tactile sensing in humans, this section presents some design hints for robotic tactile system. For a detailed study on touch sense modality and its perceptual importance in humans, see [43], [50], and [51].

A. Neurophysiology and Human Touch System

The human sense of touch deals with the spatiotemporal perception of external stimuli through a large number of receptors (e.g., mechanoreceptors—for pressure/vibration, thermoreceptors—for temperature, and nocioceptors—for pain/damage [52]) that are distributed all over the body with variable density. The response to mechanical stimulus is mediated by mechanoreceptors that are embedded in the skin at different depths. Their number, per square centimeter area, is estimated to be 241 in the fingertips and 58 in the palm of adult humans [53]. The classification, functions, and location of these receptors are shown in Fig. 3. They have different receptive fields—the extent of body area to which a receptor responds—and different rates of adaptation. A fast-adapting (FA) receptor responds with bursts of action potentials when its preferred stimulus is first applied and when it is removed. In contrast, a slow-adapting (SA) receptor remains active throughout the period during which the stimulus is in contact with its receptive field. SA-I mechanoreceptors exhibit fully tunable “stochastic resonance” [54]—a process whereby a nonlinear system is able to detect an otherwise undetectable signal (e.g., subthreshold stimulus) by adding a random stimulus or noise to the input.

The response to thermal stimulus is believed to be mediated by separate “warm” and “cold” thermoreceptor population in the skin. Nociceptor units in the skin are primarily responsible for sensation of pain; however, they also respond to extremes in temperature and sometimes to mechanical stimulation [43].

The nature of electrical discharge from various receptors in response to the external stimuli—studied *in vitro* and *in vivo* on human skin samples—is found to be pyroelectric and piezoelectric [55]. Comparative experiments on epidermis samples of skin show a marked phenomenological analogy with of piezoelectric materials [56].

B. Tactile Information Encoding and Transfer

From the moment skin is stimulated until the resulting perception, a variety of complex mechanical, perceptual, and cognitive phenomena take place. Fig. 3 shows a sequence of events during tactile signal transfer. On contact with an object, the skin conforms to its surface, maintains the same local contour, and thus projects the deformation to a large number of mechanoreceptors. Each mechanoreceptor thus represents a small portion of the object and encodes the spatiotemporal tactile information as spikes of action potentials—voltage pulses generated when the stimulus is greater than a threshold. The amplitude of the stimulus is then transformed to a train of action potentials [51]—a step similar to digitizing and coding analog signals by an analog-to-digital (A/D) convertor.

The contact event related information is transmitted to the CNS for higher level processing and interpretation via multiple nerves up to the spinal cord and via two major pathways: spinothalmic and dorsal-column-medial-lemniscal (DCML)

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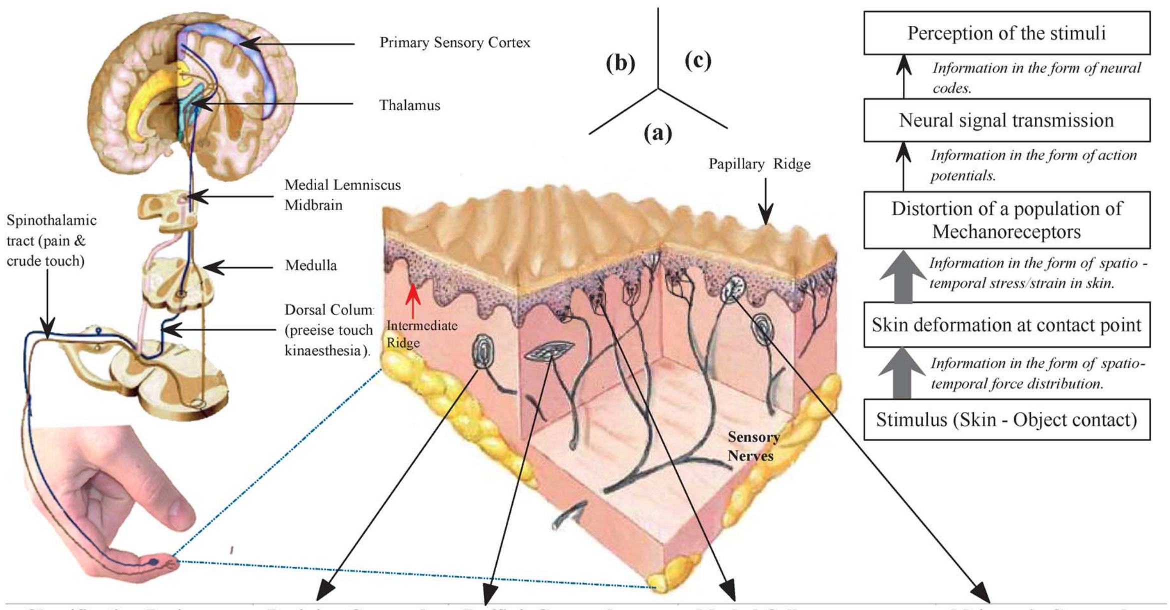

Classification Basis		Pacinian Corpuscle	Ruffini Corpuscle	Merkel Cells	Meissner's Corpuscle
Type		FA II	SA II	SA I	FA I
Adaptation Rate		Fast	Slow	Slow	Fast
Spatial Acuity (mm)		10+	7+	0.5	3-4
Vibration/rapid indent. threshold	Best(µm)	0.01	40	8	2
	Mean(µm)	0.08	300	30	6
Stimuli Frequency (Hz)		40-500+	100-500+	0.4-3	3-40
Conduction Velocity (m/s)		35-70	35-70	40-65	35-70
Effective Stimuli		Temporal changes in the skin deformation	Sustained downward Pressure; Lateral skin stretch; Skin slip.	Spatial deformation; Sustained pressure; Curvature, edge, corners.	Temporal changes in skin deformation
Sensory Function		High frequency vibration detection; Tool use.	Finger position; Stable grasp; Tangential Force; Motion direction	Pattern/form detection; texture perception; Tactile flow perception.	Low frequency vibration & motion detection; Grip control; Tactile flow perception.

Fig. 3. (a) Section of glabrous skin showing physical location and classification of various mechanoreceptors [50], [51], [57]–[60]. (b) Tactile signal transmission—from fingertips to somatosensory area of brain (modified from [61]). (c) Functional events during tactile signal transmission from contact point to the brain. For simplicity, the signal flow is unidirectional. In general, the information transfer is bidirectional as the same path is used by motor signals.

thereafter, as shown in Fig. 3. The spinothalamic pathway is slower and carries temperature and pain-related information. DCML, on other hand, quickly conveys pressure/vibration related information to the brain and helps in spatial and temporal comparisons of the stimuli. The tactile information is processed at various data transfer stages before it reaches the CNS. For example, during natural manipulations, humans can perceive independently the curvature and the direction of force from first spikes of the ensembles of primary sensory neurons in the terminal phalanx [47], [48]. This reduces the computational burden of CNS and lets it perform some higher level processing like disentangling the interactions between information obtained from ensemble of first spikes and other parameters like rate of change of contact force, temperature, change in viscoelastic properties of the fingertip, etc. [62]. The tactile information transfer to brain is also subjected to an intense process of selection [63]. For example, the tactile information is transferred when attention is paid to "which part of the body is being stroked." How the CNS combines the information from the large number of receptors to get a coherent image of objects is not discussed here; [50], [51], and [64] for further details.

C. Spatiotemporal Sensitivities of Human Tactile Sensing

Spatiotemporal limits and sensitivity to mechanical stimulus directly affect the object recognition capability [41] and directional sensitivity [65], etc. The pattern-sensing capability of the cutaneous sense is limited by both its spatial and temporal sensitivities, as they quantify the information loss or blurring of stimulus by spatiotemporal filtering at early stage of cutaneous processing [41]. Such effects can be used to define the "crosstalk" limits of robotic tactile sensors.

Spatial acuity is an important parameter that gives an idea of spatial resolution—the smallest separation at which one can tell if he/she has been touched at two points. Two points threshold [66] and grating orientation method [67] show that the spatial acuity varies across the body—from highest at fingertips, face, toes, etc., to lowest at thigh, belly, etc. The spatial resolution at the palm is about seven times smaller than that at the fingertips [68]. One can resolve two points as close as 1 mm on the fingertips [69] and up to 30 mm on the belly [50]. These results place the tactile acuity somewhere between vision and audition—worse than vision but better than audition [50]. Besides body site, the ability to perceive a fine spatial structure also depends on the temporal properties of stimulus (namely, its vibration frequency). The spatial acuity decreases if vibratory frequency is increased [70]. The spatial acuity in the torso, measured with vibrotactile stimuli, has been reported to be 20–30 mm [71]. Skin microstructures like intermediate ridges—the undulating epidermal tissues that descend into the epidermal–dermal junction (shown in Fig. 3)—also enhance the tactile spatial acuity by transmitting magnified signals from surface of skin to the mechanoreceptors [72].

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When it comes to temporal resolution, humans are capable of detecting vibrations up to 700 Hz, i.e., they can detect a single temporal interval of about 1.4 ms [43]. Comparing temporal acuity of touch with that of vision (upper limit of 50 Hz for a flickering light) and audition (20 kHz), touch again lies between vision and audition, but this time, audition is better [50]. Temporal separation of two contact events, at different locations, is also needed as it helps in detecting the presence of multiple events. The critical temporal separation for two events at different locations on fingertips is found to be on the order of 30–50 ms [73].

The pressure threshold and skin deformation are other common intensive measures of absolute tactile sensitivity. The higher the pressure threshold, the lower the sensitivity of the body part. Controlled pressure sensitive studies show that pressure thresholds vary with body site. Whereas normal mean threshold values average about 0.158 g on the palm and about 0.055 g on the fingertips of men, the corresponding values for women are 0.032 g and 0.019 g, respectively, [74].

The temperature sensitivity also varies with the body parts. For example, from a baseline temperature of 33 °C, changes as small as 0.16 and 0.12 °C for warmth and cold, respectively, can be detected at the fingertips [75]. Corresponding values at volar base of thumb are 0.11 and 0.07 °C, respectively.

D. Tactile Sensing in Perception

Humans are excellent at recognizing common objects by touch alone [76], and cues like material properties, shape, etc., are critical to this endeavor. Both cutaneous and kinesthetic sensing contribute to the perception of such cues. Tactile sensing in humans is better adapted to feel the material properties of objects than to feel their shapes—particularly when the object is large enough to extend beyond the fingertip [50]. Perhaps this is the reason why most of the studies on tactile sensibility in humans and other primates have reported sensory perception in the context of exploratory tasks [49].

Shape detection of objects small enough to be within the contact area (7–12 mm) of the fingertips is an important function of the mechanoreceptors. Experiments involving vertical indentation and stroking of skin, with the force equal to that exerted by humans during natural manipulation (15–90 g wt.), indicate that the object shape and orientation are signaled by the spatiotemporal responses of the afferent fiber populations, particularly those of the SAs [77]–[81]. The curvature and force direction can also be perceived from these signals [62]. These experiments reveal that the firing rate of an SA is a function of the vertical displacement, vertical velocity, and the amount and the rate of change of curvature of the skin. However, SAs become silent in the event of negative rate of change of curvature. In the case of FA, the firing rate is a function of the vertical velocity and the rate of change of curvature at the most sensitive part of the receptive field. These studies give a direct relation between the stimuli and neural signals that code them. Thus, assuming skin to be a "blackbox," the relation between the stimuli (e.g., the shape) and the output (e.g., the firing rate) of afferent fibers can be written as

$$f_{\mathrm{SA}} = a_1 R^{-1} + a_2 \frac{dR^{-1}}{dt} + a_3 \Delta Z + a_4 \frac{dZ}{dt} \quad (1)$$

$$f_{\mathrm{FA}} = b_2 \frac{dR^{-1}}{dt} + b_4 \frac{dZ}{dt} \quad (2)$$

where f_{SA} and f_{FA} are the firing rates of SA and FA receptors, respectively, R^{-1} is the skin curvature at contact point, ΔZ is the vertical displacement, and a_1, a_2, a_3, a_4, b_2, and b_4 are the constants. The *edge* sensitivity is a special case of sensitivity to changes in skin curvatures. As can be noticed from (1) and (2), FA and SA receptors respond simultaneously at edges and boundaries, and at other points, FA receptors are silent. The response of SA receptors is higher at edges than at a uniform surface because of high compressive strain at such points. The edge detection sensitivity of SA I receptors has also been attributed to the presence of Merkel cells on the tips of the epidermal part of intermediate ridges. Intermediate ridges are believed to magnify the tactile signals from the surface of the skin to the mechanoreceptors by way of microlever action [82], [83]. The role of intermediate ridges studied through continuum mechanics or finite element modeling also show that the concentration of stress on the ridge tips improves the capability to differentiate finer details [84]. Surprisingly, the mechanoreceptors are located close to the points where stress is concentrated. Sensitivity of receptors to the rate of change of curvature, in addition to the curvature, also enhances the contrast at the edges of objects, where curvature changes abruptly. From a robotics point of view, these results highlight the importance of having sensors that respond to both static and dynamic stimuli. A combination of capacitive/resistive and piezoelectric transduction could be one of the many possible solutions.

Roughness-smoothness is another important perceptual dimension. Neurophysiological studies suggest that the tactile roughness perception is accurately predicted by spatial variations of discharge of SA afferents, and hence, it is a function of multiple tactile elements. Contrary to the general belief that the temporal parameters have little effect on roughness perception [85], recent studies show that they indeed contribute [86]. Fingerprints or papillary ridges, shown in Fig. 3, also enhance the tactile sensitivity of Pacinian corpuscles and, hence, help in feeling fine textures [87]. Discrimination of surface roughness is also enhanced when tangential movement exists between the surface and skin [88], and this is independent of the mode (active or passive) of touch [89]. In other words, this property is salient to cutaneous/tactile sensing. Roughness of objects is significantly correlated with friction as well. The correlation is much stronger when the variations and rate of change of the tangential forces are considered. This is evident from the experiments where subjects maintained a steady normal force, rather than reducing it, to allow the tangential force to initiate and maintain sliding while scanning a surface with higher friction [90], [91]. These facts point towards the importance of tangential force and that its knowledge, in addition to the normal forces, can be useful for robotic applications.

Detection of *slip* can be viewed as the coding of motion by the receptors in the skin. Slip or relative movement between

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a surface and the skin is important for perception of roughness [85], [91], [92], hardness [93], and shape [94], [95]. Slip plays an important role in grip force control by acting as an error signal. All these, except static contact associated with thermal sensing, involve finger movements and thus highlight the importance of dynamic tactile sensing [96].

Tactile feedback from the contact surface of an object influences the perception of *force* used to support it. Experiments studying the effect of tactile sensing on the perception of force demonstrate underestimation of forces produced by muscles when tactile sensory feedback from hand is constrained [97]. Interestingly, complete elimination of tactile feedback by anesthetizing skin results in an opposite perception of force, i.e., increase in the perceived force or heaviness [98] and decrease in the maximum force that the fingers can produce [99]. Further, the effect of eliminating the tactile sensing from various fingers is also different. Elimination of cutaneous sensing from thumb and index finger results in an increase of perceived heaviness by 40% and 13%, respectively [98]. In addition to magnitude, the *direction of force* is also critical for handling objects with irregular shapes while maintaining the desired orientation. Tactile afferents from the terminal phalanx of finger contribute to the encoding of direction of fingertip forces. The directionality is also thought to be due to different strains produced at the receptor site by forces applied in different directions [49].

In context with motor control, tactile information plays an important role in controlling the execution of *reaching to grasp* movements. The contribution of cutaneous receptors for controlling prehensile force during object manipulation has been studied extensively in [52], [100], and [101]. Tactile information is used to ascertain the actual shear or load force, which then helps in optimally adjusting the grip force [52], [99], [100]. Cutaneous feedback also gives the actual state of the system; in the absence of it, internal models (of objects) underlying anticipatory control mechanisms are no longer updated during tasks like grasping [99], [102]. Various phases of a grasping action, namely, reaching, loading, lifting, holding, replacing, and unloading, are characterized as discrete sensory events by specific tactile afferent responses. In other words, signals from tactile afferents mark transitions between consecutive action phases. The planning and control of manipulation in the brain is centered on the mechanical events that mark transitions between consecutive action phases [47]. This means impaired tactile sensibility will make manipulation difficult as the brain lacks the information about mechanical contact. The touch information (along with kinesthetic, vision, and motor feedback signals) is needed to obtain the "body schema," which is an internal representation of body's structure [42].

The correct grasp of an object requires fine control of not only the strength of finger muscle activation but also of its temporal course or duration in various phases of grasp. Lack of tactile sensing lengthens the duration of the finger opening phase of the grasp, thereby impairing the control of grasp [103]. Thus, tactile information is possibly used in getting minimal duration or, in other words, in time optimization of various phases. The discharge from specific receptors at the beginning and end of a movement can be used to compute grasp time for various phases, and thus, grasp temporal parameters can be optimized [52]. In this context, taxels that are able to record dynamic events could be helpful in robotics. Tactile information from fingertips has also been shown to contribute to the control of *timing* in sequential actions such as playing a piano or tapping in synchrony to an external signal [104]. Thus, a variety of information about real-world objects is obtained through cutaneous sensing.

However, it should be noted that the human system is a complete, multilevel, integrated system, and the "sense of touch" is not isolated. Multiple sensory information from several sensory modalities like touch, vision, hearing, etc., is needed to perceive a stimulus [51]. Sometimes, the sensory modalities compete (e.g., in presence of attention), and at other times, the whole is an integrated combination of the different sensory inputs. Even if a single modality is involved, the perception of an object can be due to a combined contribution of its sub modalities. The combination and integration of sensory information from multiple sources is key to robust perception, as it maximizes the information derived from the different sensory modalities and improves the reliability of the sensory estimate. For example, the perception of size [105] and shape [106] obtained with visual and haptic information, integrated into a statistically optimal fashion, is more reliable than the unimodal estimate. Similarly, frequency content of auditory feedback can help in perceiving roughness and moistness of surfaces [107]. Both vision and proprioception provide information about the position of the hand in space [108]. Haptically and visually acquired size-related information may influence the feed-forward or anticipatory control of forces during loading and transitional phases of precision grip [109], [110]. Thus, the design of a robotic tactile-sensing system should take into account the presence of other sensing modalities and their combined role in achieving a common goal.

E. Skin Mechanics and Tactile Sensing

Skin acts as a medium through which contact indentations are converted into stresses/strains. Human skin is multilayered, nonlinear, nonhomogeneous, and viscoelastic. It is a complex structure supported on a deformable system of muscles and fat [83]. Various skin layers have different stiffness. The base epidermis layer, having Young's modulus 10–10 000 times that of dermis, is considerably stiffer than the dermis [84]. With such properties, the skin mechanics is bound to play an important role in the tactile perception. The presence of physical interlocking between the epidermis and dermis layers of skin helps in resisting any tendency of their relative sliding over each other and creates a filtering mechanism that distributes forces and stresses from their point of application [111]. Such a filtering mechanism also has considerable impact on the spatial resolution. The presence of intermediate ridges and their role in magnifying the tactile signals by way of microlever action has already been discussed. Intermediate ridges, which are shown in Fig. 3, should not be confused with papillary ridges or fingerprints that are basically the external parallel whorls. However, the center of each papillary ridge protuberance lies directly above the center of each intermediate ridge [84]. Papillary ridges are known to improve gripping [112] and tactile acuity by microlever

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mechanism [82], [83]. However, finite-element studies indicate very little involvement of papillary ridges in such a mechanism [113]. Fingerprints might improve the tactile sensitivity of pacinian corpuscles and, hence, help us feel fine texture [87]. A number of attempts have been made to model and study the mechanical behaviors of the skin; see [57], [84], [114], and [112].

F. Hints for the Design of Robotic Tactile Sensing System

Following previous discussion, some basic design criteria can be formulated for tactile sensing in a general robotic system. A few such attempts have earlier been reported in [12]–[15], and [115], and some of their findings are also included in following design hints.

1) The presence of varied and distributed receptors with sharp division of functions calls for using different kinds of miniaturized sensors—each optimally measuring a particular contact parameter (though they may help detecting other parameters as well). It is desirable to have multifunctional sensors, like contact force and hardness detection [116], and tactile and thermal sensors [117] that measure more than one contact parameter. The number of such sensing elements may depend on the body site where they are intended to be placed.
2) The spatial resolution of the tactile sensors, distributed or arranged in an array, should be based on the body site. For fingertips, it should be about 1 mm—which translates to an approximately 15×10 element grid on a fingertip sized area—and for less-sensitive parts like the palm and shoulders, it can be as high as 5 mm.
3) The sensors should demonstrate high sensitivity and wide dynamic range. Normal manipulation involves forces in the range of 15–90 g wt. [77], [78]. Considering involvement of taxels in various exploratory tasks, a force sensitivity range of 1–1000 g wt. and a dynamic range of 1000:1 are desirable [118]. The touch sensors should also be able to measure the direction of force. This is important because robots, in general, do not have a prior model of real world objects.
4) Taxels should be able to detect and measure both static and dynamic contact events. More than one mode of transduction may be required to meet such requirements.
5) The robotic tactile sensors should respond quickly. This is particularly important, if tactile feedback is used in robotic control. Involving tactile sensing in control loop of robotic applications is important due to insufficient contact information available from artificial muscles or kinesthetic sense alone. The signal frequency range to which different mechanoreceptors in human skin respond can be used to set the response time requirements of sensors. In general, for real time contacts, each touch element should respond as fast as 1 ms. The same is also true for an array of tactile sensing elements. However, such conditions can be somewhat relaxed in the case of whole body skin-type distributed taxels.
6) In humans, the tactile data is not directly sent to the brain. Instead, some processing is done at various levels to fit the limited throughput of the nervous system. Thus, to reduce the amount of information transfer to the central processing unit, it is important for large tactile arrays or modules to have some level of preprocessing (data selection, local computation, etc.) at the sensory location. Such an architecture would free "robot's brain" for more intelligent works. Alternately, it would allow scaling up the system to practically any number of sensors.
7) The contact information should be transferred via different paths with different transfer rates. The signals (mechanical) that require urgent attentions (e.g., in feedback control) can be transferred via faster path. However, such an arrangement would probably increase the number of wires—which is undesirable in robotics.
8) The taxels may also be embedded into or covered with elastic material just like the receptors in the skin that lie under different layers of skin. Although embedding the sensors in elastic material may introduce some blurring or filtering effects; the increase in contact area, as a result of such elastic covering, is helpful in manipulation.
9) The elastic covering of the sensors may be designed to have structures like intermediate and papillary ridges present in the skin. By concentrating the stresses on the sensing elements, such structures can also compensate the blurring effect of elastic cover. A textured pattern like papillary ridges on the surface of elastic material increases detectability [87], [119].
10) Biological sensors can derive information like detailed contours of objects, because the skin is compliant and conforms to object. Thus, robotic taxels should be robust, flexible, conformable, stretchable, and soft, and therefore, they can withstand harsh conditions of temperature, humidity, chemical stresses, electric field, sudden force, etc. When distributed over the body, they should not significantly increase the diameter/thickness of robot link/part.
11) Linearity and low hysteresis are also desired. Although nonlinearity can be taken care by inverse compensation, the same is difficult for hysteresis. The output of taxels should be stable, monotonic, and repeatable. It is interesting to note that the human tactile sensing is hysteric, nonlinear, time varying, and slow. However, the presence of large number of "technologically poor" receptors enables the CNS to extract useful information.

Requirements mentioned above are also application dependent and thus should not be considered definitive. Some of the above-mentioned design cues seem to be technologically challenging. Thus, technological and manufacturing issues like production of many sensing devices with similar performance (repeatability across different fabrications), type and number of interconnects, and repeatability of response over time, etc., should also be considered while designing robotic tactile sensors.

IV. Tactile Sensor Types

Tactile information is useful in robotics in a number of ways. In manipulative tasks, tactile information is used as a control parameter [120]–[122], and the required information typically includes contact point estimation, surface normal and curvature measurement, and slip detection [123] through measurement

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of normal static forces. A measure of the contact forces allows grasp force control, which is essential for maintaining stable grasps [124]. The grasp force along with manipulator displacement is also needed in compliant manipulators [125]. In addition to magnitude, the direction of force is also critical, in dexterous manipulation, to regulate the balance between normal and tangential forces, and hence to ensure grasp stability—the so-called friction cone [126]. For full grasp force and torque determination, shear information is also required [127], [128]. The need for shear stress information is also supported by finite element analysis (FEA) [129], [130]. Shear information is useful to determine the coefficient of friction and in getting a unique surface stress profile when the sensor is covered with elastomeric layer [131]. Importance of shear force in humans has already been discussed. While interacting with objects, a significant information such as shape [132]–[134], surface texture [16], [135], slip [135]–[138], etc., comes through normal and shear forces. However, a real-world interaction, involving both manipulation and exploration, also requires measuring material properties such as hardness [116], temperature [17], etc.

Taxels based on design hints presented in previous section, can possibly help in achieving some of the above objectives. Some of these design guidelines have been explored and tactile sensors exist with variable stiffness elastic layers [139], fingerprint like structures [140], and the mechanical properties and distributed touch receptors like human skin [141]. However, their number and the type of contact parameters obtained from them are still insufficient. For example, the interaction of robots with environment through tactile sensing has largely been limited to the measurement of static interaction forces, whereas real-world interaction involves both static and dynamic. Similarly, most of the sensors are designed to measure static pressure or forces, from which, it is difficult to obtain information like stickiness, texture, hardness, elasticity, etc. Recently, the importance of dynamic events has been recognized, and sensors are being developed for detecting stress changes [9], [96], incipient slip [140], strain changes [142], and other temporal contact events. A range of sensors that can detect object shape, size, position, forces, and temperature have been reported in [12]–[14], [143]. Few examples of sensors that could detect surface texture [16], [135], hardness or consistency [18], [116], and friction [144] are also described in the literature. Very few examples of sensors that can detect force as well its direction have been reported [4], [145].

Tactile sensors using nearly all modes of transduction namely, resistive/piezoresistive, Tunnel effect, capacitive, optical, ultrasonic, magnetic, piezoelectric, etc., have been reported in [4]–[35]. The way they work is described in [146], and the relative advantages and disadvantages of some of them are given in [147]. Selected examples of robotic tactile sensors based on various transduction methods and the physical/mechanical nature are discussed in the following.

A. *Tactile Sensors Based on Various Transduction Principle*

1) Resistive Sensors: Tactile sensors based on resistive mode of transduction have resistance values depending on 1) the contact location and 2) the applied force or, in other words, piezoresistance. Resistive touch sensors are generally sensitive and economic but consume lot of power. Their other limitation is that they measure only one contact location. An improved design using parallel analog resistive sensing strips, which is reported in [19], allows measuring many contact points. However, the lack of contact force measurement still remains a critical problem.

Piezoresistive touch sensors are made of materials whose resistance changes with force/pressure. The touch sensing system using this mode has been used in anthropomorphic hands [10]. Piezoresistive tactile sensing is particularly popular among microelectromechanical systems (MEMS) and silicon (Si)-based tactile sensors [20], [21]. The force-sensing resistor (FSR), which is widely used in pointing and position sensing devices such as joysticks, are also based on piezoresistive sensing technology. Commercially available from Interlink [22], they have been used in many experimental tactile systems and advanced robotic hands [148], [149]. FSRs are appealing, because of low cost, good sensitivity, low noise, and simple electronics. However, the requirement of serial or manual assembly, relatively stiff backing, nonlinear response, and large hysteresis are some of the drawbacks of FSRs.

2) Tunnel Effect Tactile Sensors: Tactile sensors based on quantum tunnel composites (QTC) have come up recently. Commercially available from Peratech [150], QTC has the unique capability of transforming from a virtually perfect insulator to a metal like conductor when deformed by compressing, twisting, or stretching. In QTC, the metal particles never come into contact; instead, they get so close that quantum tunneling (of electrons) takes place between the metal particles. Robotic hands with QTC-based taxels have been reported in [151] and [152]. A highly sensitive sensor based on electron tunneling principle is also reported in [16]. The device directly converts stress into electroluminescent light and modulates local current density—both being linearly proportional to local stress. With thin film, having metal and semiconducting nanoparticles, the sensor is 2.5 cm^2 in size and attains a spatial resolution of 40 μm—far better than that of human fingertips. However, using charge-coupled device (CCD) camera, in current form, adds to the sensor size and makes its integration difficult on the robot.

3) Capacitive Sensor: Capacitive taxels have been widely used in robotics [6], [9], [23]. They can be made very small—which allows the construction of dense sensor arrays. An array of capacitive sensors which couples to the object by means of little brushes of fibers is reported in [9]. The sensor elements on the array are reportedly very sensitive (with a threshold of about 5 mN) and robust enough to withstand forces during grasping. An 8×8 capacitive tactile sensing array with 1 mm^2 area and spatial resolution at least ten times better than humans is reported in [6]. Capacitive sensing is also popular among the tactile sensors based on MEMS and Si micromachining [4], [6], [7], [9]. Commercially available touch sensors such as "RoboTouch" and "DigiTacts" from pressure profile systems [153] and "iPod-touch" [154] are all based on capacitive technology. Availability of commercial "capacitance to digital convertor" chip like "AD7147: CapTouch" from Analog Devices [155] has made it easier to design thin and reliable contemporary touch controls for sensors that use capacitive technology. The utility of such

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a chip in getting the digitized data corresponding to change in capacitance at the contact point has been demonstrated in [156]. Touch sensors based on capacitive mode of transduction are very sensitive, but stray capacity and severe hysteresis are major drawbacks.

4) Optical Sensors: Tactile sensors with optical mode of transduction use the change in light intensity, at media of different refractive indices, to measure the pressure. Optical fiber-based taxel capable of measuring normal forces is reported in [11]. The sensor can measure forces as low as 1 mN with the spatial resolution of 5 mm. An optical three axial taxel capable of measuring normal and shear forces is reported in [8]. Some cases of large area skin based on LEDs have been reported in [157] and [158] as well. Commercial taxels using optical mode of transduction are also available, e.g., "KINOTEX" [159]. Optical-based taxels are immune to electromagnetic interference, are flexible, sensitive, and fast but at times they are bulky. For example, even after miniaturization, the optical taxel reported in [24] has diameter 32 mm, length 60 mm, and a weight of 100 g. Loss of light by microbending and chirping, which cause distortion in the signal, are some other issues associated with optical sensors.

5) Ultrasonics-Based Sensors: Acoustic ultrasonics is yet another technology used for developing tactile sensors. The microphones, based on ultrasonics, have been used to detect surface noise occurring at the onset of motion and during slip. A 2×2 tactile array of polyvinylidene fluoride (PVDF), which is described in [160], senses contact events from their ultrasonic emission at the contact point. Here, PVDF polymer is used as receiver to localize the contact point on a silicone rubber-sensing dome. The sensor is reportedly very effective in detecting slip and surface roughness during movement. Another simple and elastic tactile sensor, utilizing acoustic resonance frequency, to detect contact parameters like principal stress, friction, and slip is described in [161] and [162]. The resonant frequency of piezoelectric materials changes when they come in contact with the objects having different acoustic impedances [163], [164]. This property has been utilized to detect hardness and/or softness [18] and force/pressure [25]. Ultrasonic-based taxels have fast dynamic response and good force resolution. However, many such sensors use materials like PZT, which are difficult to process in miniaturized circuits. Using piezoelectric polymers can greatly simply such difficulties.

6) Magnetism-Based Sensors: Such tactile sensors measure the change in flux density as a result of the applied force. The flux measurement can be made either by Hall-effect device [145], [165] or a magnetoresistive device [26]. The taxels based on magnetic principle have a number of advantages that include high sensitivity, good dynamic range, no measurable mechanical hysteresis, a linear response, and physical robustness. However, their usage is limited to nonmagnetic mediums.

7) Piezoelectric Sensors: The piezoelectric materials generate charge in proportion to the applied force/pressure. Piezoelectric materials like PZT, PVDF, etc., are suitable for dynamic tactile sensing. Though quartz and ceramics (e.g., PZT) have better piezoelectric properties; the polymers such as PVDF are preferred in touch sensors due to their excellent features like flexibility, workability, and chemical stability [101]. The use of PVDF for tactile sensing was reported for first time in [14], and thereafter, a number of works based on PVDF or its copolymers have been reported in [5], [17], and [28]–[31]. Temperature sensitivity of piezoelectric materials is a major cause of concern.

B. Sensors Based on different Physical/Mechanical Nature

Most of the devices, reported in past, relied on fairly rigid materials for their construction. Perhaps this was the natural choice to start, as rigid systems are simpler and there are fewer variables to control or design. From the studies on human cutaneous sensing and the physical nature of the tissues and skin, it seems that softer materials may have much to offer. Elastic overlays and compliant contact surfaces are often advocated for their frictional and other properties, even if they exhibit low-pass filtering behavior. After examining a range of materials, with different consistencies, for impact and strain energy dissipation, conformability, hysteresis, etc. it is found that soft surfaces have more desirable characteristics for contact surfaces than hard materials [33].

Softer materials such as rubber, fluids, and powders, are now examined for tactile sensing. Among soft materials, the gels are better than plastic, rubber, sponge, or paste, with powders being the second best. Some commercial touch sensors, like those from Tekscan [179], using pressure sensitive ink or rubber are already available. A number of touch sensors using conductive rubber as transducer have also been reported [180]–[183]. However, presence of hysteresis and nonlinearity are some of their drawbacks. Conductive gels have been considered for their remarkable softness showing a 20% change in impedance for pressure 0–400 kgf/cm^2 [32]. A different use of gels involves electrorheological effects, in which, the application of a strong electric field across a suitable gel changes it from a fluid to a plastic solid. A tactile actuator on this principle together with a matching sensor is reported in [35]. A simple touch sensor, using piezoelectric effect exhibited by polyelectrolyte gels and lighting a photo diode array in response to the mechanical deformation, is reported in [34]. The fact that human tissues are also composed of electrolytic materials with very similar mechanical properties suggests intriguing possibilities for new designs of sensing fingers.

V. Distributed Tactile Sensing

Robot's guidance and force based control has mainly depended on intrinsic triaxial or 6-D force sensors. They have also been used to get the contact locations both for rigid and soft contacts [184], [185]. However, such methods are sensitive to the accuracy of force/torque sensor calibration and can provide erroneous information because of unmodeled dynamic forces [147]. Further, the compliance and inertia of manipulator may also interfere in such cases. Such problems can be reduced by having the sensors close to the contact point. In other words, by equipping robot's hands with tactile sensing arrays or extrinsic sensors distributed in a specific manner. For safe interaction, it is also desirable to have taxels all over the body. Other complementary strategies for safe interaction are the torque control [186], variable stiffness actuators [187], and soft robotic components [188]. Whole-body tactile sensing is also a

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TABLE I
TACTILE SENSING ARRAYS FOR PARTS LIKE FINGERTIPS WITH HIGH DENSITY RECEPTORS [4]–[9], [117], [166]–[178]

Year	Author	Transduction Method	Miniaturization Technique	No.of Sensing Element	Spatial Res. (mm)	Signal Condition Circuit	Sensor BW (kHz)	Range of Force$^+$(N)/ Pressure* (kPa)	Force/ Pressure Sensitivity
1984	Raibert et al.	Resistive	Si-micromachining	6x8	$\sim$0.6	Yes^a	—-	—-	—-
1985	Polla et al.	Piezoelectric	Si-micromachining	8x8	0.07	Yes^a	—-	2^+	5.2mV/gm
1988	Suzuki et al.	Capacitive	Si-micromachining	32x32	0.5	No	—-	0.01^+	0.45pF/g
1990	Sugiyama et al.	Piezoresistive	Si-micromachining	32x32	0.25	Yes^a	60	—-	0.02mV/kPa
1993	Liu et al.	Piezoresistive	Si-micromachining	4x4	1	Yes^a	—-	200*	0.032mV/kPa
1994	Audet et al.	Magnetic	Si-micromachining	—-	—-	Yes	—-	—-	—-
1996	Chu et al.	Capacitive	Si-micromachining	3x3	2.2	No	—-	0.01^+	0.13pF/g(nf) 0.32pF/g(shf)
1996	Gray et al.	Capacitive	Si-micromachining	8x8	0.1	No	—-	$1.0\times10^{-4+}$	20μN
1996	Kolesar et al.	Piezoelectric	Si-micromachining	8x8	0.7	Yes^a	0.025	$0.008–1.35^+$	—-
1997	Desouza et al.	Capacitive	Si-micromachining	16x16	500dpi	No	—-	—-	100μN
2000	Kane et al.	Piezoresistive	MEMS on Si	64x64	0.3	Yes^a	—-	35*	1.59mV/kPa
2000	Leineweber et al.	Capacitive	Si-micromachining	8x1	0.24	Yes^a	—-	100-300*	13.5mV/kPa
2002	Castelli	Capacitive	————————	8x8	>2	No	—-	120*	—-
2002	Hellard et al.	Optical	————————	4x4	>1	No	—-	—-	—-
2003	Wen et al.	Field Emission	MEMS on Si	8x8	1	Yes^a	—-	150*	30.1mV/kPa
2005	Choi et al.	Resistive & Piezoresistive	————————	24	$\sim$1	No	—-	2^+	—-
2006	Okha et al.	Optical	————————	—-	2	No	—-	2^+	1mN
2006	Schmidt et al.	FSR & Capacitive	————————	1_{static} $16_{dyn.}$	—-	No	$\sim$0.003 35	$0.05\text{-}10^+$ $<0.01^+$	5mN
2006	Takao et al.	Piezoresistive	MEMS on Si	6x6	0.42	Yes^a	—-	$0.021–0.176^+$	0.5–1V/N
2009	Dahiya et al.	Piezoelectric	Si-micromachining	32	1	Yes	5	5*	0.5V/N

^{a}Electronics circuitry (partly) on the sensing array; nf: normal force; shf: shear force.

TABLE II
TACTILE SENSING ARRAYS FOR PARTS LIKE LARGE AREA SKIN WITH LOW DENSITY OF RECEPTORS [10], [11], [156], [157], [180], [192]–[198]

Year	Author	Transduction Method	Miniaturization Technique	No.of Sensing Element	Spatial Res. (mm)	Signal Condition Circuit^a	Sensor BW^b (kHz)	Range of Force$^+$(N)/ Pressure* (kPa)	Force/ Pressure Sensitivity
1989	Cheung et al.	Optical	——————	16	—-	Yes	—-	—-	—-
1992	Domenici et al.	Piezoelectric	On Polyimide	6x7	2.5	No	—-	—-	—-
1998	Um et al.	Optical	—————-	1000	25	Yes	—-	—-	—-
2004	Someya et al.	FSR	Organic FET	32x32	2.54	No	0.003	30*	—-
2004	Weiss et al.	Resistive	—————-	3x8	4	No	—-	—-	—-
2005	Engel et al.	Resistive	MEMS on Polymer	25	$\sim$5	No	—-	—-	—-
2005	Shan et al.	Piezoresistive	MEMS on Si	4x4	10	No	—-	2^+	228mV/N(nf) 34mV/N(shf)
2006	Heo et al.	Optical	—————-	3x3	5	No	—-	5N	1mN
2006	Kim et al.	Strain Gauge	MEMS on Polymer	4x4	2.5	No	—-	0.6+	0.52V/N(nf) 0.25V/N(shf)
2006	Ohmura et al.	Optical	—————-	8x4	$\sim$30	No	—-	—-	—-
2008	Maggiali et al.	Capacitive	Flexible PCB	12	10	Yes	—-	—-	—-
2008	Mukai et al.	Piezoresistive	Flexible PCB	8x8	18	Yes	0.1	128*	—-

^{a}Electronics circuitry (partly) on the sensing array; nf: normal force; shf: shear force.

prerequisite for sensor-based motion planning algorithms [189]. Artifacts like occlusion, which is a typical problem with vision-based devices, as well can be avoided by having taxels all over the robot's body. A number of experiments showing safe human–manipulator interaction (e.g., ballerina dance with a manipulator covered with proximity sensors) have been reported in [189] and [190]. Another experiment with a full-body sensing suit, that has electrically conductive flexible fabric based taxels, is described in [191].

Over the years, many tactile sensing arrays or distributed tactile sensors schemes have been reported. Some of these works, classified on the basis of spatial resolution, are given in Tables I and II. Table I reports sensors with good spatial resolution ($\sim$1 mm)—suitable for high sensor density body sites like fingertips. On the other hand, Table II reports sensors with relatively poorer spatial resolution—suitable for low-sensor-density body sites like the palm, belly, etc. Based on the manufacturing process, the tactile sensing arrays (both, for fingertips as well as large area skin) can be grouped in two broad categories: The first involves standard miniaturization techniques, and the second does not involve them. Miniaturized taxels are generally the MEMS and field effect transistor (FET)-based sensors, realized on the rigid (e.g., Si) or flexible (e.g., plastic) substrates. The tactile sensing arrays not involving any miniaturization use off-the-shelf components distributed on flexible printed circuit boards (PCB) or embedded into a flexible substrates. Following this classification, some selected works reported in literature are discussed in the following.

A. Distributed Tactile Sensing Without Using Standard Miniaturization Techniques

By covering a manipulator with taxels, their effective usage in motion planning is demonstrated in [192] and [158]. Each of the five sensor modules used in [158] and [192] has 16 sensor pairs of phototransistors and infrared LED (IRLED). Scanning time of each module is 20 ms (serial access within a module), and it is the same for all the five modules (parallel access among modules). Thus, a rate higher than the velocity commands update rate (36 ms) of PUMA robot was obtained, and the sensor data could easily fit into the real-time operations performed by manipulator. IRLEDs were primarily proximity sensors, and thus, real contact was avoided. Even though realistic situations require touching the objects, for the first time, this work demonstrated that motion planning can be done with no *a priori* knowledge about the dynamic environment.

A 32-element lightweight, conformable, and scalable large area skin using optical mode of transduction is presented in [157]. Each taxel consists of photoreflector covered by urethane foam. The light scattered by urethane foam upon deformation gives the measure of mechanoelectrical transduction. Scan time of each sensor element is 0.2 ms, and spatial resolution is approximately 3 cm. A major disadvantage of this method is the large current needed by LEDs (∼50 mA per sensing element). Tactile sensors using similar method are also commercially available from KINOTEX [159]. Another optical-based 3×3 tactile sensing array, using wavelength division multiplexing (WDM) technology to quantify the stimuli, is reported in [11]. In WDM, the shift in wavelength of the returned signal gives a measure of the stimuli.

A stress-component-selective tactile sensing array, based on piezoelectric polymers is presented in [193]. This multicomponent touch sensing array consists of an assembly of seven elemental subarrays, each consisting of six miniaturized sensors, supported by a polyimide sheet and sandwiched between two elastic layers.

Stretchable tactile distributed sensors based on electrical impedance tomography (EIT)—a noninvasive technique used in medical applications—is presented in [199]. In this method, a conductive material with electrodes on its boundaries is used as taxel. On injection of current via electrodes, the pressure-sensitive sheet translates the pressure distribution over its surface into impedance distribution, which is then measured using EIT. A thin, flexible, and stretchable taxel, which is suitable for movable joints, can be obtained with this method. The reported tactile sensing arrays are capable of detecting stroking, pinching, and grabbing and can be used to detect forces as small as 1 N. However, the requirement of continuous current injection (and hence loss of energy) is a major concern that will hinder effective utility of this approach, especially in the case of autonomous robots that rely on battery power.

A 16×3 array of taxels, with the wire electrodes stitched into the pressure conductive rubber, is reported in [181]. A pitch of 3 mm has been obtained. The delay between input and output is reported to be 1 ms. However, it is expected to go up if the time taken by rubber to regain the original shape is also considered. Further, pressure conductive rubbers have nonlinear relation between the applied load and resistance.

Conformable sensor patches that can be interconnected to create a networked structure are presented in [156] and [198]. Both the triangular-shaped patches (each with 12 capacitive touch sensors) reported in [156] and the 64 pressure-sensing element patch reported in [198] have been realized on flexible PCBs. In these works, the transducers and signal conditioning electronics wrap the robot surface and microcontroller units are installed in the inner body. Off-the-shelf components are used for embedded electronics. The proposed sensor patch in [156] has low power consumption (∼5 W/m^2). However, the 3–5-mm-thick silicone foam needed in [156] and 5-mm-thick elastic sheet used in [198] blurs the tactile information.

B. *Tactile Sensing Arrays Involving Standard Miniaturization*

The tactile sensing arrays involving standard miniaturization can be further categorized as

1) those developed with "MEMS on Si" [172], [177], [196], [200], [201] and "MEMS on plastic" [195];
2) those with Organic FETs (OFETs)/FETs/thin film transistors (TFTs) realized on organic/Si/elastomeric substrates [5], [178], [180], [181], [202], [203], and tightly coupled with the transducers.

MEMS-based tactile sensors generally use a capacitive [4], [6], [173], [200], [204], [205] or piezoresistive [172], [177], [206] mode of transduction. While piezoresistive devices offer higher linearity, the capacitive devices are an order of magnitude more sensitive. The early works on piezoresistive and capacitive micromachined sensors, like those presented in [207] and [208], have produced arrays of force sensors using diaphragms or cantilevers as the sensing elements. MEMS-based tactile sensing array, with taxels connected in a piezoresistive bridge arrangement, have been used to detect the shear force [172]. MEMS devices realized by Si micromachining are quite sensitive and result in higher spatial resolution. However, inherent fragile and brittle nature of Si limits their utility in practical robotic systems [11] because they Cannot withstand the forces/pressure experienced during normal manipulation. Packaging of MEMS-based taxels has also been a challenging issue. A Si-based piezoresistive force sensor that addresses the problems of robust packaging, small size, and overload tolerance is reported in [20]. The sensor measures the force applied to a 4 mm raised dome on the device surface exhibits a linear response, good repeatability, and low hysteresis and has a flexible and durable packaging. Another drawback of MEMS approach is the difficulties involved in realizing flexible tactile sensing arrays on a Si substrate. A novel method of obtaining MEMS-based flexible sensing device is reported in [177]. In this work, the Si diaphragm has sensing pixel array on it and a pressure chamber beneath. The diaphragm is swollen like a balloon by the pressurized air provided to the chamber through the hole. The stiffness of the diaphragm is thus controlled by the air pressure. This way, contact forces in the range of 2.1–17.6 gf are measured with air pressure in the range of 5–64 kPa. However, the extra provisions for air supply and its monitoring are quite cumbersome and as such the arrangement is unsuitable for robotics.

Recent technological advances allow us to realize MEMS-based devices on plastic substrates—an alternate way for obtaining flexible MEMS sensors. Multimodal tactile sensor arrays able to measure hardness, thermal conductivity, temperature, and the film curvature have been realized using

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plastic-MEMS [195]. The sensing array reported in [195] is an attempt towards measuring contact parameters other than force/pressure. However, like many others, these arrays too suffer from the wiring complexity, and the utility is limited by the scalability of the wiring interconnects.

An interesting development in the area of tactile sensing is the concept of "sense and process at same site." Traces of this concept can be found in technologies like extended gate [203], [209], polymer or organic electronics [180], [195], and thin-film Si circuits (e.g., TFTs) on foils or elastomeric substrates [203], [210]. Besides improving the signal to noise ratio, the approach has potential of reducing the number of wires—a key robotics issue. Though potential use of some of these technologies has been demonstrated in a number of applications like flexible displays, smart fabrics, etc., their use in sensitive skin has been limited. Some of these works are discussed in the following.

A 32×32 element, OFET-based touch-sensing array realized on flexible polymer substrate is reported in [180]. The taxels, using pressure sensitive rubber as transducer, have a pitch of 2.54 mm. Response time of each OFET is 30 ms, and that of pressure sensitive rubber is typically of the order of hundreds of milliseconds. Thus, taxels do not respond to the higher frequency signals. Replacing pressure-sensitive rubber on OFET with polymers like PVDF can improve the transducer related performance. However, the overall response time and the pitch will still be quite high with respect to the devices obtained with standard IC technology. The large time response of OFETs is due to inherently low charge-carrier mobility—best organics have a mobility of about 1 $\text{cm}^2/(\text{V}\cdot\text{s})$ versus 85 $\text{cm}^2/(\text{V}\cdot\text{s})$ for MOS technology [210]. If such an array is thus placed on the fingertips, then both high pitch and the requirement of fast response would limit the number of taxels on the array. However, features like physical flexibility and lower fabrication cost make them good candidates for large-area skin [211], [212]. This is also true in view of the fact that spatiotemporal requirements can be somewhat relaxed for body parts other than fingertips.

Piezoelectric polymers are also widely used due to their high sensitivity and availability in form of thin films of various thicknesses. A tactile sensing array ($9200 \times 7900\ \mu\text{m}^2$), with symmetrical 8×8 matrix of electrodes ($400 \times 400\ \mu\text{m}^2$ each), epoxy adhered with a 40-μm PVDF film is reported in [5] and [209]. The method is essentially an extended gate approach, similar to one reported in [167], [213], and [214], where electrodes are directly coupled to the gate of MOSFET amplifiers (ON or OFF the chip having electrodes). The spatial resolution of these arrays is less than 1 mm, the taxels have linear response for loads spanning 0.8–135 gf (0.008–1.35 N), and the response bandwidth of 25 Hz is reported. These sensing arrays also possessed minimal on-chip processing circuitry—single MOS transistor with each transducer—and used an external electronic multiplexer to scan the array in less than 50 ms. The problem of response stability and reproducibility, which is traditionally associated with piezoelectric-based tactile sensors, is taken care by a precharge bias technique [28], which involves initializing the sensors before each cycle. Using a similar approach, 32-element tactile sensing arrays, epoxy-adhered with 25-, 50-, and 100-μm piezoelectric polymer film (PVDF-TrFE), are reported in [178]. The arrays reportedly have 1 mm spatial resolution, and the taxels have been tested for dynamic forces up to 5 N in the frequency range of 2–5kHz. The capability of tactile arrays to identify objects based on their hardness also has been demonstrated.

The extended gate approach brings the sensor and analog front-end closer, and hence, overall response is better than a conventional approach, in which the sensor and analog sensors front-end are separated by some distance. However, the extended gates also introduce a large substrate capacitance between the polymer film and the gate terminal of the FET device, which in turn, significantly attenuates the charge/voltage generated by the sensor and increases the propagation delay [164]. In this context, the tactile sensing arrays using an advanced piezoelectric oxide semiconductor field-effect transistor (POSFET) technology are expected to be better. In POSFET-based approach, piezoelectric polymer is directly deposited on the gate of MOS devices [215], [216].

Like MEMS on Si, the lack of physical flexibility is a major disadvantage of tactile sensing arrays realized on Si, using standard IC technology. Due to this reason, the touch sensing arrays presented in [178], [164], and [209] are more suitable for fingertips. However, they can also be used like skin over larger area by making a conformable electronics surface with a soft and compliant polymer substrate, having mechanically integrated but otherwise distinct and stiff sub circuit islands of sensors connected to each other by flexible and stretchable metal interconnects. Other possible trade off could be the introduction of mechanical compliance by covering the chip with an elastic layer of silicone. Low thermal conductivity of such elastic materials also reduces the noise (if any) introduced by ambient temperature variations. However, a careful study is needed as such materials suffer from creep, hysteresis, and, in practice, work as low pass filters [182], [217]. In addition, the presence of elastic layers aggravates the inversion problem by offering more than one solution during the process of regenerating the stress distribution at the contact area.

Advances in Si-based thin-film technology makes it possible to fabricate lightweight, stretchable, and foldable integrated circuits from rigid semiconductor wafers with performance equal to established technologies [202], [210]. CMOS inverters and ring oscillators with such properties have been fabricated by integrating inorganic electronic materials, including aligned arrays of nanoribbons of single crystalline Si with ultrathin plastic (polyimide) and elastomeric [Polydimethyl siloxane (PDMS)] substrate [202]. The first elastic and stretchable transistor circuit, which is made by mounting TFT on polyimide foil islands on elastomeric substrates and configured with patterns of stretchable metallization, is reported in [203]. These implementations demonstrate the feasibility of fabricating high performance, elastic, stretchable, and foldable Si active circuits on electronic skin. With transducers like piezoelectric polymers, such active circuits can offer many interesting solutions, like distributed computing, for the sensitive skin.

Circuits using OTFTs [180] are flexible and conformable but are not known to fold or stretch like those based on Si [202]. In terms of performance, OTFTs and other nontransistor-

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based [157] tactile sensing arrays are inferior to their Si-transistor-based counterparts. However, they are better placed in terms of fabrication cost. While some real-time robotic applications may require high performing (e.g., faster taxel response as well as reading the tactile data in a time lesser than update rate of controllers) taxels, for others, the performance may not be the real issue. Different technologies have their respective advantages and disadvantages in terms of fabrication cost, performance, physical, and mechanical properties, etc. There is no unique technology that can meet all requirements of whole body skin and a combination of different technologies should be pursued. A kind of merge, with elements from various sensing technologies integrated in a single electronic skin, will be an interesting development.

VI. Tactile Sensing System—Issues and Discussion

Tactile sensing, which is limited to fingertips and hands until the last decade or so, has been extended to the whole body, as is evident from the increasing number of tactile sensing arrays that are reportedly more suitable for whole body skin. In this transition from fingertips to whole body, many unsolved issues have been left behind. While good strides have been made in robotic hand design [39], [152], [218], in reality, the tactile sensory information required even for dexterous manipulation lags behind the mechanical capability of the hands.

Despite innovative designs, a large number of taxels have been rendered “bench top,” as the emphasis has been on the sensors, and the system has largely been ignored. This is evident from Tables I and II, which show only few tactile sensing arrays with any kind of electronic circuitry on chip with sensors [5], [166], [167], [169], [170], [172], [173], [175], [177], [209]. Those having any, possess circuitry with minimal complexity, e.g., a single MOS transistor associated with each transducer [172], [209]. Very few tactile sensing arrays with mixed mode (analog and digital) implementation have been reported [166], [169], [170]. The design of taxels and finally their integration on the robot is a result of many tradeoffs. Instead of inventing “yet another touch sensor,” one should aim for the tactile sensing system. While new tactile sensing arrays are designed to be flexible, conformable, and stretchable, very few mention system constraints like those posed by other sensors, by the robot controller, and by other system aspects like embedded electronics, distributed computing, networking, wiring, power consumption, robustness, manufacturability, and maintainability. Such issues are important for effective integration and usage of the taxels on a robotic system. While some of these issues have been discussed in [157], [189], [190], [194], [219], and [220], others arising out of existing hardware and software, especially in case of humanoid robots, are discussed here.

A general hierarchical functional and structural block diagram of a tactile sensing system is shown in Fig. 4. The complex tactile sensing process has been systematically divided into subprocesses, which helps in designing different parts to a desired level of complexity. The levels from bottom-to-top depict the sensing, perception, and, ultimately, action. The arrows from bottom-to-top show flow of contact information and from top-to-bottom shows the addressing of various sensors. Addressing of taxels is helpful in experiments such as the study of the cognitive behavior of a robot when “attention” is paid to a particular body site. The flow of signals in the functional block diagram is somewhat similar to that of human tactile sensing system. The system constraints, at various levels of Fig. 4, are discussed in the following paragraphs of this section.

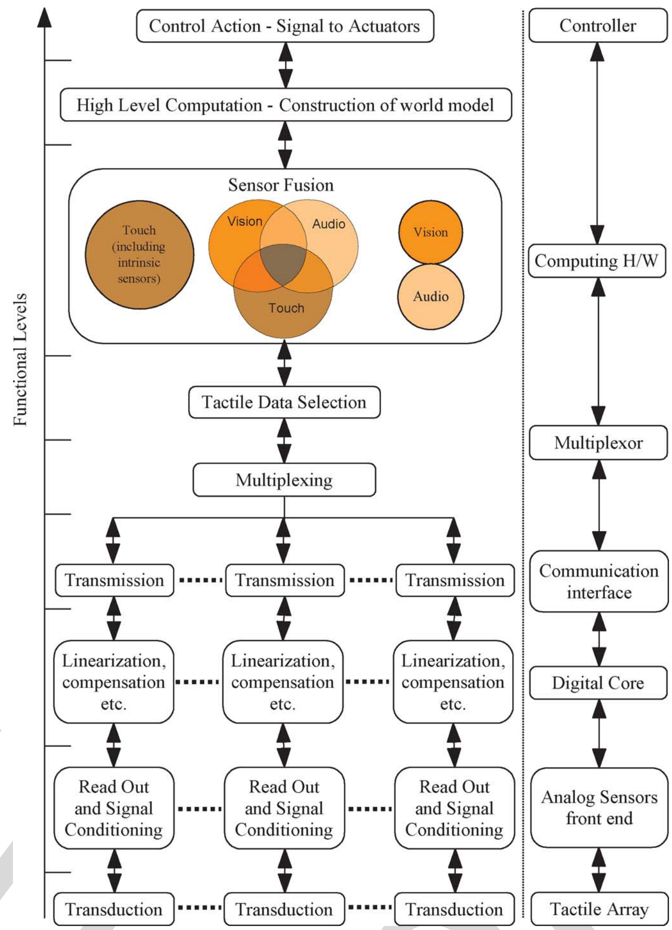

Fig. 4. Hierarchical functional and structural block diagram of robotic tactile sensing system [219].

Transduction of contact data constitutes the lowest level of the tactile sensing system shown in Fig. 4. It involves measurements like magnitude and direction of forces, distribution of force in space, stress and stress rate, temperature, etc. An accurate reconstruction of contact details requires a sufficient number of sensing elements within the available space, which places a constraint on the choice of the transduction method. Measuring multiple contact parameters may require simultaneous use of more than one mode of transduction. For example, both stress and stress rate can be measured with a sensor that is a combination of capacitive/resistive and piezoelectric transduction. The choice of transduction method is also important in terms of time response. A poor choice of a transduction medium can result in a sluggish response of the tactile sensing arrays, as in [166] and [180]—where the need to use piezoelectric materials is felt to improve the response time. Existing sensors, e.g., joint force/torque sensor, vision sensor, etc., and the update rate of the

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controller on the robot may also set the limits of time response. The transduction method also places a constraint on the number of sensors that can be used in an array. For example, the pressure conductive rubber used in [180] has a time response of the order of few hundreds of milliseconds and OFETs have a response time of 30 ms. With an active matrix and scanning of one word line at a time adopted in [180], an array with 16 × 16 sensing elements can be scanned in 480 ms, which is comparable to the response time of the transducer, and hence, 16 × 16 is the upper limit of the elements in the array. Power requirements also influence the choice of transduction method. Ideally, the transducer should not consume any power. Consumption of large amount of power, as in optical transduction-based sensing arrays reported in [157], is definitely a cause of concern when using such arrays on an autonomous robot that relies on battery power.

The need for a suitable *signal conditioning* circuitry, to process the analog data, has always been felt. The right choice of transduction method and conditioning circuit is important as they set the bandwidth limits of the data accessed by the higher levels of the tactile sensing system. Barring capacitive touch sensors, for which small A/D convertor chips are commercially available, e.g., AD7147 [155], dedicated A/D convertors chips are not available for tactile sensors using other transduction modes. The analog sensor front end and digital core (see Fig. 4) needed to process and digitize the analog data are essential parts of the tactile sensing system. Design of these components greatly depend on the chosen transduction method. Processing the large amount of data from distributed taxels has often figured among the major reasons for neglecting tactile sensing *vis-a-vis* other sense modalities [36]. In humans, as discussed earlier, the brain does not receive the raw contact data from receptors; instead, part of it is processed at receptor level—indicating the presence of "sense and process at same site" scheme. In a similar manner, the analog sensor front end and digital core can be designed to perform some low-level computations like simple scaling, segregation of data from different kind of touch sensors, (e.g., force, temperature, etc.), linearization, compensation (like temperature compensation, if sensor performance changes with temperature), compressing of information, slip detection, and texture recognition, etc. Such distributed computing architecture would reduce the amount of data and help in optimum usage of the limited throughput of robot's processing unit. This will free the "robot's brain" for more intelligent works. Otherwise, it allows scaling up the system to practically any number of sensors. A system on chip (SoC) or system in package (SiP) would be ideal in such a case. Besides improving the performance, the SoC/SiP approach can also help in reducing the number of wires. It will also result in a tactile analog of CMOS optical arrays/imagers. CMOS imagers have played a significant role in bringing vision sensing to satisfactory levels, and the same can be expected for tactile sensing. While the SoC/SiP approach has benefited closely related application domains like smart fabric [221] and smart vision [222], it is surprising that robotic tactile sensing has largely remained untouched.

The amount of wires needed to *read and transmit* the data from a large number of taxels is another key issue. The number of wires has some inverse relation with dexterity and some direct relation with the time needed to scan a set of taxels or array. Fewer wires call for the serial access of data, which is slower than parallel access—that requires a large number of wires. If the real-time contact profile or image is of interest, then serial data access may fail to produce a "snap-shot" of the image, and the image may be distorted—if the real time contact conditions change faster than the scan rate. Reading dynamic contact events is also difficult if the transducers have fast decay time, as in piezoelectric transducers. Novel techniques like using local memory, as in "active pixel" of CMOS visual imagers [223], can help in improving the scan rate while reading the data serially. The amount of improvement in the scan time can be gauged from the fact that with "active taxels"—analogous of active pixel—an array of 16 × 16 sensing elements in [180] could be read in 480 ms (reading one word per line with 30 ms for each row), which can otherwise be as high as 7.68 s, when read serially one after another. The read-out time of other sensors in the control loop and the update rate of the controller may also be used to set the limits to read a set of taxels.

The *transmission* of tactile data is normally done with serial buses. The desired operation speed, noise, and number of wires put a constraint on the type of communication channel used to interact with higher levels. The buses using a controller area network (CAN) protocol are generally preferred due to better real-time capabilities, high reliability, and availability on most microcontrollers. However, CAN buses have moderate transmission bandwidth (up to 1 Mb/s), which either results in slow transmission of large tactile data or puts a cap on the number of taxels. Alternate solutions include using buses with higher transmission bandwidth (e.g., FlexRay with up to 10 Mb/s [224]) or more buses in parallel—which is undesirable. Transmission issues can be reduced by judiciously placing the sensors and restricting their number without compromising the kind of tactile information they record [225].

Wireless data transmission would be an ideal solution to the wiring complexity. It will also make it easy to use stretchable and flexible touch sensing arrays, which otherwise require flexible and stretchable interconnects. Although some progress has been made on flexible interconnects, like gold film conductors on nanopatterned elastomeric substrate [226], it is still insufficient for large area sensing applications like whole body skin. Very few works using wireless communication for touch sensing have been reported in [227] and [228]. On the flip side, the interference among large number of closely placed taxels and large amount of power are issues with wireless transmission. A wireless power transmission, as in flexible wireless power transmission sheets [229], may prove to be handy. Despite all technological advances in wireless communication, the safety issues, when robots and humans work alongside each other, pose a big hindrance and question its reliability over the wired data transfer. Connection schemes like net structured taxels [183] provide alternative solutions to wiring complexity.

Data selection is another way of reducing or optimally using the tactile data. Data from all taxels may not be useful, and hence, redundant data should be rejected. For example, a grasp may not involve all the fingers, and hence, the data obtained from the fingers other than those involved in the grasp can be

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rejected. As shown in Fig. 4, data selection can be performed somewhere between the lower hardware intensive functional levels and the upper computational intensive levels.

To *construct the world model*, the data from different sensory modalities needs to be integrated, as is done in humans [105]. In humanoids the data could come from touch, vision, or audio sensors or a combination of any of these [230]–[232]. Correct integration of the signals from different sensors is important for perception—which calls for compatibility among the sensing hardware. As mentioned earlier, efficient vision, audio, and intrinsic force sensors are commercially available. Thus, assuming their fixed configuration, a compatibility constraint is placed on tactile sensors. In general, transducer materials suffer from fatigue, which results in a changed response over a period of time. Such variations result in calibration issues which can be mathematically fixed, using suitable algorithms, at the highest computational intensive levels of Fig. 4. This way, the life of the sensors can also be increased. For a reliable control of complex tasks, parameters like sensor density, resolution, and location are particularly important, and thus, low levels must be designed keeping these in mind.

Besides these, the manufacturing of reliable, economic, and flexible tactile system having compact wiring etc. are other technological issues. A modular approach [157], [189], [194]—with components like transducers, read out, analog sensors front end, and digital core in each module—can be an economical and reliable solution. Maintenance is also easier with a modular approach, as only malfunctioning modules need replacement. Due to variability in functional and spatiotemporal requirements of various body sites, location specific modules can be useful—though components like communication interface can be similar, to contain the overall cost.

VII. Conclusion

A number of studies have been described, showing how tactile signals are used by the brain to explore, perceive, and learn the objects that eventually help in manipulation and control. The ways in which biological systems process sensory information to control behavior may not always lead to the best engineering solutions for robots; nevertheless, they provide useful insights into how behaving organisms respond to dynamically changing environments and also provide a comprehensive multilevel conceptual framework within which to organize the overall task of designing the sensors for robotic systems. Hence, some design cues—inspired from human tactile sensing system—have been presented and used as desiderata for the robotic tactile sensors, for arrays, and more generally to build an electronic skin. A number of technologies and transduction principles that have been used for the development of tactile sensing for robots have been presented. It is felt that despite experimenting with a broad spectrum of transduction technologies and innovative designs, tactile sensing has not made much headway. This could be due to the lack of a system approach and a mix of technological difficulties. The technology often does not scale up to complete systems (multichannel, distributed, flexible, resilient), and consequently, the realization of a full-blown skin is not even considered. While mechanically flexible, conformable, and stretchable taxels and sensing arrays are in vogue, the emphasis has still remained on the sensor development rather than on the system development. System aspects like embedding electronics, distributed computing power, networking, wiring, power consumption, robustness, manufacturability, and maintainability also need attention. In particular, wiring remains a key issue. The absence of any tactile analog to the CMOS optical array has often been felt as one of reasons for the slow development of tactile sensing *vis-a-vis* other sense modalities [147]. A successful implementation of tactile sensors arrays with promising approaches like "sense and process at same site" and SoC/SiP can possibly provide a tactile analog of CMOS optical arrays.

Overall system performance is dictated not only by the isolated quality of the individual system elements but also by the way they integrate. In the words of Aristotle, "the whole is more than some of its parts." Taking into account various system constraints while designing the tactile sensing devices can be very useful in their final integration with a robot. This requires understanding of the sensor system architecture at various levels—right from sensing the external stimulus until the action as a result of the stimulus. Much work needs to be done at the system level before artificial touch can be used in a real-world environment. Inclusion of signals from tactile arrays in the control loop of a robot will help in exploring deeper issues involved in exploration, manipulation, and control. This will serve as a basis for the development of practical and economic tactile-sensing systems in the future. An effective inclusion of touch sensors on touch-sense-impoverished robots will not only advance research in robotics but will also help understand the human interaction with the environment.

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