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Skin-Like Sensor Arrays

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CONTENTS

1. OVERVIEW

Skin, as the surface covering the outermost layer of animals and objects in general, constitutes a specialized, complex system where body-external world interactions take place and interplay.

Surface phenomena are, as a general rule, more complex than bulk-based properties and interactions. It is not surprising that human skin, although being visible, extended, exposed and easily accessible possibly represents the least known and underscored body organ. Radiative and contact-mediated external stimuli are captured and transduced at the level of skin: electromagnetic, mechanical, thermal and chemical energy inputs are transformed into real world information content. The functions of "skins" largely encompass the information-gathering (sensing) role; evolution has found innumerable ways of adapting and exploiting outer surface layers for very diverse functions ranging from energy harvesting and thermal control, protection from insults, but also exchange with the external environment, camouflage and even surface-mediation of mobility (gecko pads, shark skin, birds feathers, etc.).

In the last decades engineers have started to systematically investigate ways to capture skin features to enable the design and implementation of devices and system exploitable in a large variety of man-made artefacts, "smart skins," spanning from airplanes, to buildings and bridges, to robots and machines in general [1].

In this chapter we limit our focus to "skin-like sensor arrays" and their mechanical information gathering role; a field which can be said to originate, at the level of wide engineering community, in the early 80's of last century with the pioneering analysis and seminal work of Leon D. Harmon [2] on touch sensing technology in automated manufacturing. Previous work was essentially confined to the niche area of prosthetics.

Large area, flexible arrays of sensors with data processing capabilities and specific feature extraction algorithms have been specifically conceived and designed to sense interactions between bodies and the external environment. Although tactile sensors have not often been designed by explicit bioinspired concepts, the very functional properties of biological skins underpin the mimicry efforts of engineers in this field.

In this chapter we restrict our focus to contact sensing modalities of thermal and mechanical nature (tactile sensing) and to more recent pioneering work on artificial kinaesthesia. The combination of these modalities opens up research avenues in the rapidly growing field of haptics which implies integration of skin-like sensing and kinaesthesia to lead to active touch operations.

A relatively extended introduction to tactile and haptic functions in humans (and primates in general) is provided since they represent the ultimate goal when developing skin-like sensor arrays. However, the complexity of somatosensory functions and coupled motor actions and their peripheral and central integration is enormous and far beyond any present engineering realization.

2. BIOLOGICAL TACTILE AND HAPTIC PERCEPTION

The high degree of dexterity which characterizes grasping and manipulative functions in humans, and the sophisticated capability of recognizing the features of an object are the result of a powerful sensory-motor integration which fully exploits the wealth of information provided by the cutaneous and kinaesthetic neural afferent systems.

It is customary to refer to tactile sensation when dealing with cutaneous spatiotemporal discrimination. The term haptic is used primarily when referring to tactile perceptual

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operations which also depend on kinaesthetic response and active object manipulation [3]. Kinaesthesia concerns the perception of joint or limb position and movement, and in the broadest sense it also defines the related sense of force.

2.1. Biological Tactile Sensing

Tactile functions are most effective at the fingertips, where detection of the surface texture of an object and discrimination of its fine form are performed by a large number of elaborate corpuscular and free nerve endings sensitive to mechanical stimuli (mechanoreceptors). A tactile unit is a combination of a peripheral sensory neuron and its specialized receptors. Tactile units can be classified into four major classes according to the extension of their receptive field and on the basis of their adaptation characteristics (i.e., the response to a sustained indentation of the skin) [4].

Approximately 44% of mechanoreceptors are found to be slowly adapting (SA) (i.e., they also respond with a sustained discharge to static tissue deformation), while the remaining are fast adapting (FA), only responding to the rate of skin indentation and its higher derivatives. Depending on the extension of their receptive fields, SA and FA tactile units can be subdivided into two categories: type I have restricted and sharply defined receptive fields and type II have larger fields and less precise contours. The correspondence between SAI and Merkel's complexes, FAI and Meissner corpuscles, SAII and Ruffini's endings, and FAII and Pacinian corpuscles is widely accepted (see Fig. 1).

The primary neural events underlying tactile sensations are a complex combination of spatial and temporal coding mechanisms in various mechanoreceptors populations (see Section 3). Spatially distributed neural patterns account for bidimensional reconstruction of embossed surfaces, while a nonspatial coding mechanism operates when detecting very fine surface discontinuities and texture [5].

Psychophysical studies have shown that the limiting spatial resolution at human fingertips is of the order of 1 mm or slightly less, a figure which fits well with the local innervation density of SA and FAI receptors.

Neurophysiological studies (mostly performed on monkeys) have shown that SA receptors are responsible for fine form discrimination and they define the limits of spatial acuity when the object is presented passively to the fingertip and

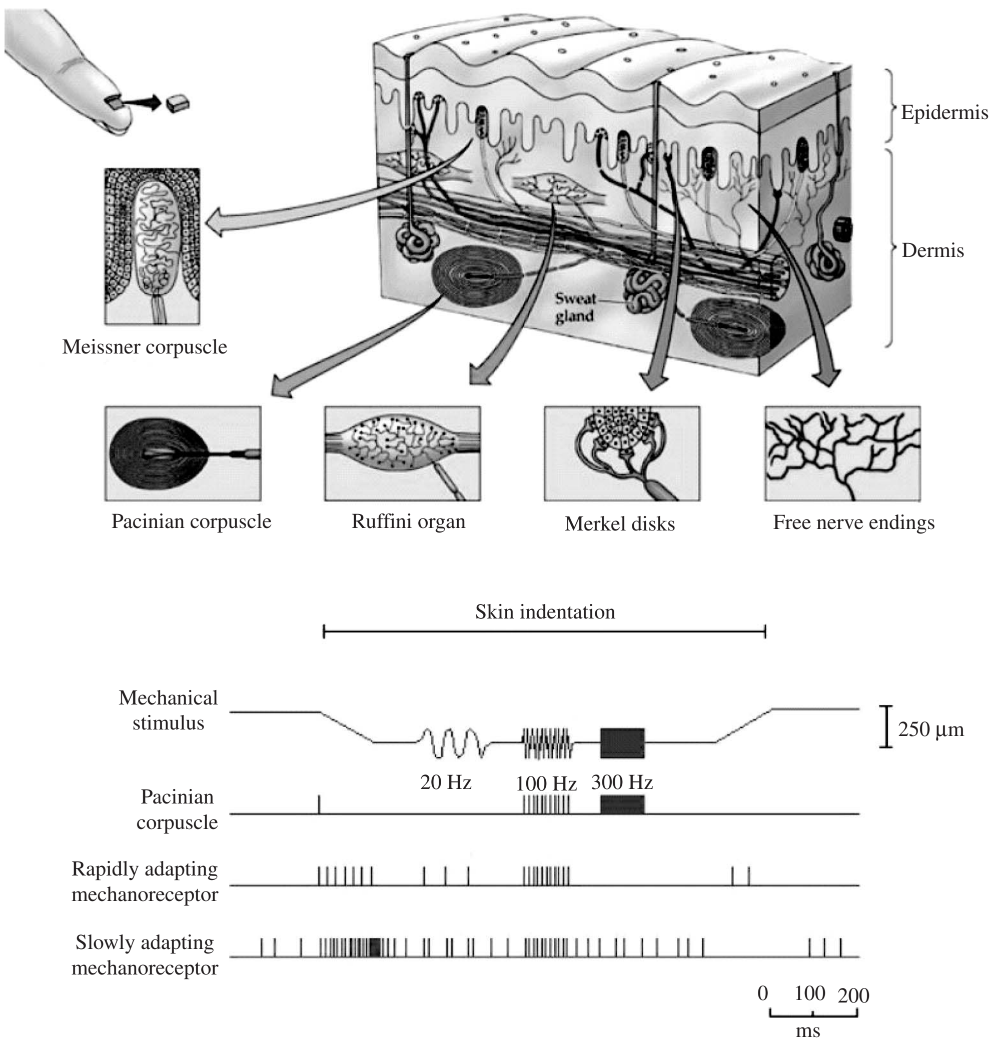

Figure 1. Organization of mechanoreceptors in the skin (upper) and firing rate of mechanoreceptors following an external mechanical stimulus.

when scanning procedures are actively performed. Scanning, moreover, considerably increases contrast, providing more intense spatial images.

The role of primary spatial system has been ascribed to SAI receptors being responsible for fine form and texture perception when the fingers contact an object, and perception of external events through the profile of skin indentation caused by the pattern of spatially distributed pressures across the pliable and compliant skin surface [6].

FAI receptors too are involved in coding spatial information, but their resolution is lower (>3 mm) and their contribution in spatial discrimination is not yet well understood. A role of FAI's has been shown in detection of flutter, mechanical transient events (i.e., slip, motion across the skin), and very minute surface discontinuities [7]. Patterned surfaces with spatial periods below the limits of spatial acuity (<1 mm) clearly fail to produce spatial images, nevertheless they are discriminable. Hypotheses have been formulated attributing the perception of texture to a coding process which depends on the relative activation of different mechanoreceptor populations induced by vibration caused by surface transient deformations. These fine textures evoke vibrations to which the tactile system is very sensitive. FAIIs are more sensitive to higher frequencies (about 60–400 Hz), FAI are very sensitive in the 5–200 Hz range, and SA afferents in the 0–100 Hz range [8]. Receptors of the FAII and SAII type are deeply located in the dermis, subcutaneous tissues and in the most fibrous tissues throughout the body.

2.2. Biological Mechanisms in Kinaesthesia

Skin, joint and muscle receptors provide the bulk of our kinaesthetic sensation from the limbs [9]. FA receptors are natural candidates to detect all movement features, though little is known about which specific receptors are actually operating and related peripheral coding.

Receptive mechanisms underlying static joint position are easier to investigate. Sophisticated receptors in muscles provide a fundamental input: muscle spindles lying in parallel with the main (extrafusal) muscle fibers measure muscle length and rate of change in length through corresponding changes in the receptors (intrafusal) muscle fibers. Knowing the length of muscles around a joint would allow determination of joint position. Besides sensory innervations, spindles are endowed with multiple motor innervations which the Central Nervous System (CNS) utilizes to independently control both the length and rate response of the receptors (intrafusal) muscle fibers, preventing spindles from supplying absolute information about muscle length values.

Thus, true muscle length and velocity signals are not available to the nervous system from muscle discharges alone, even if the majority of the proprioceptive information derives from muscle spindles. Hypotheses have been formulated on an additional central processing necessarily implied, but there is no evidence to rule out other mechanisms the CNS might utilize to encode proprioceptive peripheral information.

Neuroscientists tend to favor the view that the CNS could monitor its own motor commands to muscles and spindles generating, through central feedback pathways, a copy of the efference, used to decode peripheral muscle signals. According to the equilibrium-point hypothesis [10, 11] central commands might define a reference point and scaling of the afferent activity from peripheral receptors reflecting joint torque change. Joint torque as related to both central commands and external load conditions is taken to be a crucial cue for kinaesthetic discriminations. Muscle spindles could code the relevant information since their afferent activity reflects differences between externally (load conditions) and internally (fusimotor activity) imposed change on receptors. Furthermore, other load detectors (tendon organs, joint receptors) contribute to a parallel processing of proprioceptive information arising from different peripheral sources.

At a joint, muscles are arranged in opposing groups: in every movement we make some muscles shorten and other lengthen. For a muscle which crosses more than one joint, many combinations of joint positions could, in principle, correspond to the same muscle length and tension. Ambiguity can be resolved only if the CNS refers also to signals simultaneously delivered by other muscles which cross only some of those joints.

2.3. Kinaesthesia at the Hand

The hand is an exception to the rule above. Since the long flexors and extensors of the fingers are multiarticular spanning at least one interposed joint and no monoarticular muscles move the interphalangeal joints, lengths of the extrinsic muscles cannot have an unambiguous relationship with the angle of individual finger joints at least in a flexion-extension plane. Assuming that individual joint angles are the relevant proprioceptive quantities the sensori-motor system utilizes, one is compelled to look for sources of supplementary information.

For this purpose, joint receptors do not appear to play a significant role. Since muscle receptors alone cannot subserve an adequate sensation, a proprioceptive role for cutaneous receptors in fingers is widely accepted.

Several cutaneous mechanoreceptors might signal kinaesthetic information when movement at a joint stretches and bends regions of the skin around the joint. FA receptors may provide movement signals, but a sense of static joint position requires SA receptor types. It was shown that only SAIIs (Ruffini's endings) respond well to skin stretch, but their number is too small to account for adequately encoding joint angle values [10].

Using a method that provides assessment of static position sense independently of movement sense, lack in discriminating joint static position was shown in the proximal interphalangeal joint of the index finger [13]. However, length information from receptors in the extrinsic muscles seems sufficient to adequately estimate location of the fingertip relative to a fixed wrist position in an investigation with a biomechanical model of the human long finger and forearm muscles which actuate it, suggesting that quantities other than individual joint angles could constitute the relevant information in kinaesthetic sensing [14].

Anaesthesia at the fingertip, but not in skin around a moving joint, reduces proprioception in that joint as well as anesthetizing the thumb impairs kinaesthetic detection of the index finger, indicating thus some sort of facilitatory input even in regions away from the moving part. Convergence connections are not limited to sensorial information since a close interaction for the thumb and the index finger also emerges as a facilitatory functional connection between the tactile sense and (supraspinal and spinal) motor mechanisms accounting for the control of certain finger movements [15]. Such interactions do not extend to other body parts and seem to constitute a unique feature confined to the hand. They appear as fragments of powerful integration between the rich tactile apparatus in the skin with a large corresponding representation in the somato-sensory cerebral cortex and motor cortex with the pyramidal tract of fundamental importance in the control of fine finger and hand movements. A collection of cortical body representations of increasing integrating complexity could constitute the neural substrates of the human haptic perception.

2.4. Haptic Perception

Proprioception in human fingers more than sensing individual angles in some joints (the interphalangeal) seems oriented toward estimating, and conceivably controlling, location of the fingertips where the highest density of cutaneous receptors exists and tactile discrimination capabilities are most effective.

While tactile and kinaesthetic sensing exhibit remarkable ability of fine-grain sensorial analysis, information from peripheral mechanoreceptors must be combined in some coherent fashion to synthesize an unified motor-perceptual image of the hand in object manipulation and recognition.

For the invoked internal model, hypotheses have been formulated that a systematic combination of functionally convergent local sensations might be processed as a set of computational procedures by specific neural network in localized areas of the brain.

In cytoarchitectural areas of higher level projections from regions of the skin of the hand that tend to be stimulated together when objects are held or manipulated (i.e., skin covering the tips or the volar surfaces of multiple adjacent fingers, entire regions of the palm, etc.) converge into large individual receptive fields. These tactile cortical neurons respond to specific stimulus features (i.e., motion across the skin, direction of motion, contact areas in adjacent skin surfaces) extracted in synthetic form from large populations of receptors. In the same way, among cortical neurons that process information from posture and movement of the hand, a large number of multiple joint neurons exist encoding not individual joints, but unique coordinated postures (i.e., multiple phalange flexion as observed in grasping) of adjacent joints in a finger and of adjacent fingers in the hand. Discharges from neurons that in preference respond to contact with objects when they are actively grasped have been collected in relation to movements of the monkey's hand recorded through video imaging. These "haptic" neurons appear integrate at even higher level tactile and kinaesthetic information in object manipulation.

In neuroimaging studies in humans, cerebral areas involved in haptic discrimination tasks have been identified using positron emission tomography (PET) [17]. In discriminating pairs of objects on the basis of surface microgeometric (roughness) and macrogeometric (length) properties, it was shown that both tasks activated overlapping cortical areas in the contralateral (with respect to the exploring hand) somato-sensory cortex. In length discrimination, however, activated fields are more extended and also include areas in the motor cortex as well as in other distant cerebral regions. The different activation patterns, where roughness discrimination involves only a subset of the cortical fields activated when recognizing object's spatial features, are taken to be due to the differences in the information needed to perform the task.

From a neurophysiological point of view, little is known in humans about actual signals from tactile afferents and corresponding central processes in real exploratory tasks. More is known about actual signals from tactile afferents in certain manipulative tasks. When lifting rougher or more slippery objects in a grip between the thumb and index finger, the CNS organizes a parallel change in the grip and lifting forces which produces a constant ratio precisely adapted to the frictional conditions between skin and object in order to ensure a safety margin for a stable grasp and controlled sliding [18]. Just after the contact, but before lifting force generation, tactile afferents begin to tune appropriate motor output and, on occurrence, release automatic motor adjustments to prevent slip. Anaesthesia at the fingertips alters adaptation to frictional conditions, but not the parallel change of the normal and tangential forces at the contacts.

Here some clinical observations appear of interest. In reconstructive surgery at the hand transfer of volar innervated skin, together with muscles and tendons, has been found to be essential for a successful rehabilitation of haptic executions [19]. Conversely, when a loss of proprioceptive and tactile information occurs, thus disrupting haptic perceptions and actions, great difficulties for such common tasks as eating, drinking or dressing himself even under visual control have been observed [20].

Our present knowledge of haptic perception is fragmentary. An understanding of how perceived object features relate in a percept and shape motor behaviors appropriate to the task is still lacking. As a consequence replicas and practical implementations in technical devices of human haptics in all its essential features are far from reach.

3. MODELING SPATIOTEMPORAL MECHANISMS OF MECHANORECEPTOR RESPONSE IN TOUCH

The primary neural events underlying tactile sensations are a complex combination of spatial and temporal coding mechanisms in various mechanoreceptor populations whose limits appear to be set by peripheral, not central, factors. Purely empirical approaches (see Section 2) to the reconstruction of the neural response of a single mechanoreceptor class or even the simplest applied stimuli involve major studies and their findings are not amenable to generalizations. Most recent studies have thus been directed at formulating mechanistic, predictive models of the response of different mechanoreceptors.

Modeling the peripheral mechanisms underlying spatiotemporal tactile transduction should pass through at least three major levels of conceptualization:

(a) equilibrium and transient solutions of contact mechanics problems applied to the skin;
(b) formulation of appropriate transfer functions at the receptor level to describe the conversion of the local tissue strain or strain rate into neural electrochemical transients; and
(c) description of the temporal events in the spatiotemporal neural discharge patterns (the coding problem).

Formulating a model on these lines is a formidable task considering that no satisfactory constitutive equation far skin tissue is available under general loading conditions, that the molecular aspects of electromechanochemical conversion are unknown and that the terminal mechanisms of the mechanoreceptor are not even accessible to standard methods of electrophysiological measurement.

The few attempts to model the general problem necessarily rely on a bottom-up approach in which a few very simple starting assumptions are formulated and then modified according to experimental evidence.

Moreover, the modeling problem has often been decoupled by separating the response of the receptor into localized vibrations (temporal input) and into the more complex task of modeling fine form discrimination (spatial input).

A combination of the two approaches leads to the analysis of the surface quality (texture) discrimination capabilities of the tactile senses, when scanning movements are performed.

3.1. Response to Temporal Stimuli

Many studies have focused on the Pacinian Corpuscle (PC) because of its large size, relatively easy accessibility and low detection threshold.

The extensive studies on the structure and functions of PC [21] have allowed the formulation of several mechanistic models of its transduction characteristics in terms of equivalent electrical circuits.

Similar models have been used, after suitable tuning of parameters, with the intent of describing the response of other mechanoreceptors, including both SA and FA classes [22].

The temporal patterns of the receptor responses show a transition frequency from an almost random to a regular behavior. These frequencies have been found to be 5 Hz far SA, 7 Hz far FAI and 110 Hz far PC.

Features that are consistently observed and correctly predicted by the model are:

(a) the impulses generated are restricted to a small temporal fraction of the stimulus cycle (i.e., the response is phase locked);
(b) the impulse phase advances with increasing stimulus intensity; and
(c) in the regime of regular behavior, the probability of an impulse generated by the receptor in a cycle of vibratory stimulation is dependent on the response on previous cycles.

SA, FAI and PC receptors also present the same general relationship between neural impulse rate and amplitude of the vibrotactile stimulus (measured as skin indentation depth). Stimulus amplitude I less than a threshold value I_0 does not evoke any neural response, while amplitudes higher than I_1 produce a saturation response of 1 impulse per cycle of the vibratory stimulus.

For amplitudes I in the intermediate range tram I_0 and I_1 the impulse rate grows (in a linear or sigmoidal manner) from 0–1 impulse per cycle.

The sensitivity of PC to stimulus amplitude is higher than that of SA by one or even two orders of magnitude, depending on stimulus frequency, while FAI show sensitivity slightly higher or comparable with that of SA.

The frequency dependence of the sensitivity curves in the (I_0, I_1) range is somewhat complex to analyze in its details, with SA showing a peak in sensitivity at low frequencies (around 5 Hz), FAI in a medium range (10–40 Hz) and PC at higher frequencies ($\geq$80 Hz).

3.2. Response to Spatial Stimuli

There are essentially two different mechanisms at work when the tactile system discriminates objects on the basis of spatial details characterizing fine form or surface texture.

Spatially distributed neural patterning accounts for bidimensional reconstruction of embossed surfaces, while a nonspatial coding mechanism operates when detecting very fine surface discontinuities and texture.

Edge enhancement and surrounding suppression are performed at the level I of SA receptors providing a form of local "early computation," while extensive receptor branching accounts far the improved spatial resolution observed in discriminating complex shapes and far interreceptor interactions.

FAI receptors are also involved in coding spatial information, but their resolution is lower (>3 mm) and their role in spatial discrimination, when performed by activating movement, is not yet well understood.

The human ability to distinguish surface texture through scanning procedures cannot be accounted for by spatial coding mechanisms alone. Hypotheses have been formulated in which the perception of texture is based on a coding process, somewhat analogous to color coding in vision at the level of the cones, which depends on the relative activation of different mechanoreceptor populations induced by vibrations caused by surface discontinuities [3].

In the most comprehensive modeling effort to date [23], the subcutaneous state of stress and strain is calculated under paradigmatic loading conditions by using continuum mechanics and the local strain is compared with neural discharge patterns of various mechanoreceptor populations under conformal experimental conditions, to identify the effective component of the stimulus.

Despite the fact that the adopted assumptions are quite crude, several important experimental findings are faithfully reproduced by the model. The following conclusions can be drawn by the study:

(a) for the loading conditions which have been considered (indentation depth $\leq$1 mm), skin can be reasonably approximated as an ideal elastic medium of semi-infinite extent;
(b) the superposition principle can be assumed to hold when the stimuli are defined by applied force;

(c) the subcutaneous tissues are in a state of plane stress and SA receptors are selectively sensitive to the local maximum compressive strain; and
(d) FAI receptors have been found, although with much less conclusive evidence, to be sensitive to the maximum horizontal strain in a region of the order of about 3 mm in diameter.

4. BASIC MECHANICS AND TACTILE SENSING FEATURES

Considerations based on kinematics and dynamics of rigid bodies and contact mechanics are fundamental to the analysis and design of artificial skin-like sensing systems. Although these disciplines are well established, their application to machine grasping and tactile sensing has been limited, and only in the last years have reports of specific studies on the subject appeared in the literature.

The considerations reported here are limited in scope, addressing specific tactile sensing modalities in somewhat idealized conditions and purposely directed at clarifying design issues and dimensioning criteria.

4.1. Grasp Kinematics and Kinaesthetic-Like Sensing

Much of the early work on grasping has looked at contact between objects and end-effectors on the basis of purely kinematic arguments [24, 25]. The primary goal of these studies was to define criteria for selecting internal grasp forces (those to be applied by the end-effector actuators) to ensure stable grasp, thus avoiding object sliding or damage.

Contact models assumed in such analyses are idealized point, line, planar and "soft-finger" contacts. Salisbury [26] proposed a method of obtaining the set of contact information that is most relevant to those models. Salisbury's original method consists in contact sensing based on the measurement of resultant force and torque remote from the contact area, and applies exactly to only point-type contacts. The theory of "intrinsic" contact sensing has been largely improved, and exact results for the general case of compliant fingertip-object pairs (soft finger type contact) are available [27].

The salient features of intrinsic contact sensory systems are that the contact force is sensed in both its normal and tangential (friction) components, as well as the friction torque resisting rotational slippage. Moreover, concise information on the location of contact is given, in terms of a characteristic point (the "contact centroid") which lies inside the smallest convex portion of the fingertip surface enclosing all of the contact area.

As a consequence, however, when extended line or planar contacts occur, the line or surface of contact cannot he uniquely located unless "active sensing" is performed. This procedure implies successive sensor readings during small exploratory motions between the tip and the object, whilst maintaining contact.

Typical implementations of such sensors consist of a multiaxis, miniaturized force-torque sensor, placed inside and coupled with the fingertip cover that contacts the environment.

4.2. Modeling Friction and Incipient Slippage Detection

Kinematic design is a powerful methodology in grasp modeling as discussed in the previous section. However, neglecting dynamic aspects of the contact and adopting oversimplified assumptions on the deformation and frictional behavior of finger-tip materials necessarily leads to unrealistic predictions of the internal forces in end-effectors and poor grasp performance.

Several devices have been described, capable of detecting slip between a grasped object and the end-effector, Tomovic and Stojiljkovic [28] reported the construction and use of a slippage sensor made of miniature spheres incorporated into compliant protective layers, whose rotary motions, induced by a sliding contact, can be detected electronically. Other authors used different transduction effects to reveal sliding contacts, such as acoustic emission [29], vibrations detected by photoelastic elements [30] and skin accelerations [31]. All these sensors, however, detect a signal that is generated only when relative motion has already occurred, considerably reducing their usefulness in servoloop grasp control.

More recent research work has therefore addressed the problem of analysing sliding phenomena when more realistic frictional models of interaction between compliant finger-tips and objects and dynamic factors of contact are considered.

Only after taking these aspects into account may more stable grasp modalities be conceived and may controlled sliding [32] between fingers and objects, necessary in dexterous manipulation, be better quantified.

The requirements of relatively large contact areas and deformable gripping surfaces, made of rubber-like materials for stable grasp, force the analysis beyond the single-point and line contact modalities and coulombic friction.

The price to be paid is a rather complex analysis and additional difficulties related to the determination of contact conditions that are no longer uniquely determined.

Cutlosky and Wright [33], having discussed noncoulombic frictional models for compliant, rubber-like materials in contact with rigid bodies, have performed a simplified dynamic analysis of contact modalities; obtaining limiting conditions which prevent rolling and slipping under linear shear or torsional stresses.

Howe et al. [34] examined the behavior of soft and very soft finger contacts under combined torsion and linear shear loading and identified slipping limits using a model in which friction is assumed to he proportional to normal force to the power 2/3. They reported a simple, operative sliding limit as:

$$f_t + A \cdot |m_n| \leq \mu \cdot |f_n|$$

where f_t and f_n, are respectively the tangential and normal contact forces, m_n, is the spinning moment, μ is the coefficient of friction and A is a proportionality constant between the torsion and shear limits, which is a function of the contact radius. Different modeling approaches permit the estimation of A, which is strongly dependent on contact geometry.

A more rigorous analysis of incipient sliding under tangential loading [35] takes into account the irreversible nature of these phenomena and the onset and dynamic changes of "stick" and "slip" contact regions. When, in a non-conformal contact with friction, tangential loading is superimposed on normal contact forces, tangential surface tractions arise, causing "microslip" to occur at the edges of the contact area where tangential traction is high and normal force is low. A "stick" region develops in the central zone where tangential traction is lower and normal force higher. A further increase of tangential forces under constant normal loading will cause the "slip" region to propagate inward and the "stick" region to shrink until surface tangential tractions can no longer be sustained and the object starts to slip.

From the discussion above it follows that incipient slippage detection, for ensuring stable grasp by servo gripping forces, cannot be performed by kinaesthetic-like sensing alone.

Distributed skin-like tactile sensors, capable of resolving normal and shear contact forces and permitting the estimation of size and location of contact area, are necessary for ensuring stable grasp and controlled sliding in manipulation.

Canepa et al. [36] have investigated on tactile sensors for incipient slip detection. Incipient slippage has been detected by the progressive shape changes of the stress spatial distributions inside the sensor block due to an incremental tangential load acting on the pressing body, while maintaining a constant normal load [37].

To detect the incipience of slippage a sensor that is able to measure two components of the internal stress field generated by the contact with different objects has been developed. It consists of a linear array of eight couples of piezoelectric polymer transducers: one transducer of each couple is sensitive to a combination of normal stresses, while the other detects the shear stress along the direction of the array.

Normal and shear stresses components inside the sensor are the input data of the neural net. An important feature of the system is that the *a priori* knowledge of the friction coefficient between the sensor and the object being manipulated is not needed. To validate the method both simulated and experimental data were used. In the first case, the Finite Element Method was used to solve the direct problem of elastic contact in its full nonlinearity by resorting to the lowest number of approximations regarding the real problem. Simulation showed that the network learns and is robust to noise. Experimental results showed that, in a simple case, the method is able to detect the incipiency of slippage between an object and the sensor. Although more work has to be done along this line, experimental results are very promising.

4.3. Contact Mechanics and Fine-Form Discrimination

A primary motivation for the development of high-density tactile sensor arrays resides in the intent to replicate cutaneous sensing features dedicated to resolving and categorizing fine spatial details of an object's profile, i.e., its fine form.

Fearing and Hollerbach [38] have introduced and analyzed problems and suggested methodologies to detect the actual contact stress generated by object contact at the surface of a compliant pad covering the finger. Determining contact force was shown to be more significant than indentation profiles in planning grasping forces. The contact stress at the finger surface was calculated by using the measured, discrete spatial distribution of stress or strain in a plane located beneath or embedded in the compliant elastic pad. The problem, so formulated, belongs to the class of inverse problems of elastic contact, where the force distribution acting on the boundary of the sensor should be inferred from spatially discrete knowledge of the stress field over a surface inside the sensor. This problem, however, is an ill-posed one in which the existence, uniqueness and stability of the solution are not guaranteed, and only through suitable constraints, formulated on the basis of physical considerations or complementary information, may a solution eventually be found [39].

A few research groups have addressed this problem by conceiving and developing both suitable sensor arrays and inversion methodologies and algorithms. The problem is usually modeled as a frictionless, non-conformal contact occurring between a rigid indenter and a semi-infinite elastic, homogeneous, isotropic medium.

Limited classes of indenter shapes are used paradigmatically and direct problems of elastic contact are usually formulated as mixed boundary value problems and solved to obtain the strain in the medium in terms of surface stresses, indenter profile and resultant load.

Linear functional equations are obtained in the form.

$$Tx = y$$

where x and y are real functions and T is a bounded integral operator with smooth kernel.

Since the tactile sensor array can provide only a spatial sampling of stress (or strain) on a plane, and the surface stresses or indenter profiles are to be obtained as discrete samples, the inversion method consists in solving linear equations associated with discrete convolution as a generalized inverse solution:

$$x_0 = T^{-1}y$$

where x_0 is a vector of dimension equal to the number of surface samples and y is a vector whose dimension is equal to the number of sensors. T^{-1} is the inverse operator.

De Rossi et al. [40] reported faithful reconstruction of axially symmetric indenter profiles by numerical algorithms based on regularized solutions of inverse elastic contact problems, through discrete inverse operators. A stress-component-selective sensor array made of piezoelectric polymer elements and hybrid circuitry for amplification and multiplexing is used in this study. Solutions of the inverse problem were based on the definition of a class of approximated inverse operators through which a priori knowledge of the solution were used to stabilize the inversion process. Making this choice means to favor, among all the functions that give a good enough fit to the data, the one with minimum norm and first derivative.

Simulation performed using input data from the theoretically solved direct problem showed accurate reconstruction of indenter profiles (conical, parabolic, flat-base circular) even in the presence of Gaussian noise added to the data.

Pati et al. [41] have described an approach to tactile inversion based on neural network principles. A triaxial piezoresistive silicon array and a dedicated neural processor on a VLSI chip were implemented. Reconstruction of surface stresses generated by a cylindrical indenter, accomplished by a neural network employing a maximum entropy deconvolution, was fast and accurate. A plain stress (plain stress) contact situation was considered leading to a convolutional contact model; the problem can be analyzed by linear space-invariant system concepts, and the inversion (deconvolution, in this case) was accomplished by a minimum entropy Hopfield-like neural network.

A completely non conformal contact was considered by Caiti et al. [42], hence the problem to be solved is fully non linear and stated in terms of a functional approximation. In particular two possible neural networks have been considered: one is based on Radial Basis Functions and can be linked directly with the analytical investigation of the inverse problem, and the other is based on Multi Layer Perceptron with sigmoid-like activation functions and trained by means of the back-propagation algorithm. In both cases, the inversion results show accurate shape reconstructions and robustness to noisy simulated data and to the real measurements provided by the sensor.

4.4. Probing and Grasping of Textured Surfaces

Humans make extensive use of surface textural information for object classification, feature extraction and for adapting gripping forces.

Waviness and roughness sensing rely upon active tangential exploration in which mechanoreceptors and their associated neural processing extract averaged topographical features of surface asperities. The characteristic spatial wavelength of the surface features is much less than the spatial acuity of the tactile sensing apparatus.

Some psycho-physiological studies of texture detection, aimed at identifying exploratory procedures adopted by humans performing specific recognition tasks, have also been motivated by the need to implement artificial haptic systems [43].

Machine sensing of regularly textured and rough surfaces, however, has been seldom studied though often mentioned.

A few reports of a descriptive nature have addressed the capacity of different tactile sensors to probe surface texture.

Bajcsy [44], in an articulated approach addressing the problem of reconstructing shape from touch, reported modalities and results on texture detection of different surfaces and materials using tactile sensor arrays with low spatial resolution moved tangentially across the object surfaces. Coarse texture was well discriminated through the temporal pattern analysis of sensor element responses.

Dario et al. [44] described a single-element piezoelectric sensor whose compliant, dome-shaped tip acts as a sort of distributed pick-up capable of converting texture spatial wavelengths into temporal signals under sensor-object sliding motion. A small set of grooved and embossed metal surfaces were probed and discriminated.

Early work on these lines, however, has not provided any clue to the parameters and features to be extracted by roughness detection. Moreover, no report on the information analysis and coding needed for their actual use in object manipulation by machines appears to be available.

In contrast, careful studies of a general nature on the analysis and classification of surface texture have been performed and their effects on the results of classical contact theory (smooth surfaces in continuous contact) carefully evaluated. Waviness and roughness detection is, to be sure, useful in object discrimination, but its role is far more relevant in planning and performing gripping and controlled sliding in manipulation.

In case of objects with wavy surfaces, it is crucial to determine the evolution of real contact area under varying contact forces. Changes in the ratio of real to apparent (nominal) contact area with normal contact loads have been analyzed theoretically and experimentally [35].

For an isotropic, wavy surface in contact with an elastic half-space, experimental data and numerical solutions of contact equations have been reported [46], permitting the evaluation of the load-varying contact area.

It is worth noting that the classical Hertz theory of contact predicts, in this case, that the real area of contact grows with the normal load to the power 2/3. It should not he surprising that the same law holds approximately for rubber in light contact with rigid bodies. Hertz theory, however, only provides asymptotic results at very low surface traction; at higher contact pressures the area of contact grows faster than predicted by Hertz theory.

Surface texture can be analyzed using this methodology when the amplitude of the surface undulations is small with respect to their characteristic spatial wavelength.

In the case of grasping objects with rough surfaces, assessing topographical features which condition contact behavior would again be a valuable sensorial modality for an artificial manipulation system.

Roughness detection for explorative and discriminative purposes (for example in object selection) should be based upon sound topographical descriptions of rough surfaces and realistic models of transduction phenomena.

Average roughness along a line segment L is defined as

$$R_a = \frac{1}{L}\int_0^L |z|dx$$

where z is the local asperity height referred to the surface center-line.

Useful parameters are the standard deviation σ_s of the height of the surface from the center-line, the root-mean-square slope σ_m and the root-mean-square curvature σ_k of the surface profile (or the mean summit curvature $\bar{k}_s$).

When rough surfaces are pushed into contact, their behavior is governed by these (or derived) quantities and by the asperity density η_s. The analysis of profilometer traces and the derivation of the quantities above have been investigated by Greenwood [47], and the reader should refer to this paper for a detailed account.

It is quite unlikely that data for an accurate analysis of surface roughness could be provided by even sophisticated and specialized tactile sensors. However, more pragmatic approaches should be adopted by identifying relevant features in spatio-temporal patterns of the signal generated by surface tangential exploration.

More relevant to artificial manipulation is the analysis of the effects of roughness on conformal and non-conformal contact. In the case of conformal (planar) contact with a randomly rough surface the effects are well known [48]. Amonton's law of friction states that the real area of contact grows in direct proportion to the normal load, and a coefficient of limiting friction can be used in defining criteria for slip avoidance.

A more complex situation occurs in elastic contact of rough non-conformal surfaces. Greenwood and Tripp [49] extended the Hertz theory of elastic contact to rough surfaces and found that Hertzian results are valid at sufficiently high loads, but at lower loads the effective pressure distribution is much lower and extends much farther than for smooth surfaces.

Deviations from Hertzian behavior caused by surface roughness can be large, depending primarily on adimensional parameters which can be calculated for paradigmatic conditions.

Although these two factors may influence planning and control of grasp forces considerably, their inference from measurement and quantification of surface roughness appears to be problematic in tactile sensing and strongly affected by modeling complexity and inaccuracy.

A more reasonable approach to account for surface roughness in object manipulation would possibly reside in monitoring the dynamics of "stick" and "slip" regions, as discussed in Section 4.2.

More recently, Tada et al. [50] have developed a soft fingertip with distributed sensors and its ability to sense the texture of the object. The soft finger is basically imitating the structure of a human finger, which is, consisting of epidermal and dermal layers. Several strain gauges and PVDF (polyvinylidene fluoride) films are embedded randomly in the fingertip.

Preliminary experiments show that the fingertip can detect the difference between the textures of the object by two PVDF films thanks to the skin dynamics between them.

4.5. Rheology and Assessment of Bulk Material Properties

Assessing bulk material properties of objects, such as hardness, has attracted some interest because of its relevance to the tasks of classification, selection and manipulation.

The level of reported activity does not appear to be significant, however, and the few reports addressing these aspects are preliminary and often only of a qualitative nature.

Even scarcer is the research and development work performed by the robotic community on machine psychorheology. Psycho-rheology, a discipline whose methodologies and techniques are aimed at interpreting haptic sensations associated with properties such as "consistency," "body," "tack," etc. and at replacing subjective human judgements with instrumental measurements, has experienced major progress mostly with the pioneering work of Scott-Blair [51].

Hardness evaluation was carried out by Bajcsy [44] by pressing a robotic finger, sensorized with a low spatial resolution tactile sensor, against the object: this was performed in small incremental displacement steps, and by reading the sensor output during the loading and subsequent unloading processes.

Material hardness was ranked according to the slopes of the linear parts of the loading and unloading sensor outputs. No details were given about loading and unloading speeds.

Although discrimination of different materials was reported to be successful, it is unlikely that the procedure and devices that have been used will lead to true measurements, even in terms of ordinal scales. Work along similar lines was reported by Bardelli et al. [52] using a single-element sensor made of a piezoelectric polymer pressed against flat sheets of rubbery materials of different compliance and backed by a reference load cell. Hardness ranking was associated with the slope of the straight line obtained in the sensor output-reference cell signal plane under loading.

More significant work has been reported by Kato et al. [53], as an initial step toward realizing artificially the recognizing function of softness similar to that in human hands. They prepared samples of polymeric materials with different viscoelastic behavior, and psychophysical test responses were associated with the output of an automatic indenting apparatus purposely designed and constructed to classify and quantify viscoelasticity.

A good correspondence between ordinal and ratio scales [54] constructed in the psychophysical study and the output of the apparatus led the authors to formulate claims of the machine's perception of softness.

Bicchi et al. [54] have been focused on the haptic task of discriminating different objects by their compliance, and on the realization of a system for allowing an operator to remotely perform such operation, i.e., a remote haptic system (RHS). An RHS is comprised in general of a *telemanipulator*, allowing the human operator to perform exploratory actions on the remote specimen, and a *haptic perceptual channel*, conveying back information to the operator.

A new psychophysical hypothesis to convey haptic information has been proposed. More precisely, it has been conjectured that a large part of haptic information necessary to discriminate softness of objects by touch is contained in the law that relates resultant contact force to the overall area of contact, or in other terms in the rate by which the contact area spreads over the finger surface as the finger is increasingly pressed on the object. This relationship was called Integral Tactile Flow Paradigm. This new conjecture takes inspiration from optic flow concept in the vision field and in particular from the time to collision phenomenon. It was found out, indeed, a similarity between the growing rate of the contact area between the finger pad and an object during a tactile indentation task and the convergence or divergence of the vision field in time to collision task. Tactile flow is based on the conjecture that if perpendicular motions in vision provide information on approach velocity, perpendicular motions in tactile manipulation provide information on compliance. In order to further validate this hypothesis, fMRI investigations are planned to verify whether tactile flow is neurophysiologically coded by the same cortical areas of the brain responsible for the optic flow. This new paradigm should be helpful in designing improved haptic devices for sensing and displaying. Several early prototypes have been realized and a set of experiments validating their performance has been performed.

4.6. Heat Transfer and Thermal Sensing

Human thermal sensing is an additional exteroceptive function for material discrimination, as it is not only used for temperature sensing. Differences in thermal conductivity and diffusivity in objects at the same temperature are perceived by thermal receptors since they govern the heat flux through non-isothermal skin. Thermal sensing in robotics has been investigated by using single-element [52] and array sensors [56]. Pyroelectric and thermistor arrays, backed by a thermostated heat source, have been used to measure dynamic maps of temperature changes generated by contact between sensor and object. Discrimination among different materials was obtained with fairly good accuracy.

Thermal sensing through contact heating was suggested to be useful also in object shape recognition [57]. In addition, shape recognition by a pyroelectric tactile sensor array was demonstrated through object shadowing under radiant heating [58].

5. SKIN-LIKE SENSORS ARRAYS AND THEIR APPLICATIONS

From the pioneering efforts of the early 80's skin-like sensor arrays have undergone considerable shifts of emphasis in terms of key areas of application. The early focus on automated manufacturing is now essentially disappeared and past predictions [2] have not been realized. It is true that still today most of tactile sensing devices did not move out of laboratories or, at best, found very small niche application areas. Several reasons can be found to account for this fact [59]. More recently, ambient intelligence, autonomous agents and artificial haptics have become research areas of major interest where skin-like sensor arrays may play an important role. Rehabilitation and surgery, service robotics and material product handling are sectors which may greatly benefit from technical and methodological advances in the field.

5.1. Skin-Like Sensing in Prosthetics and Orthotics

The development of more efficient prosthetic and orthotic systems intended to substitute for or help in restoring lost mechanoreceptive and manipulative functions because of injury or disease now depends on major breakthroughs in artificial tactile sensing technology and biological interfaces.

Strict requirements of cosmetic and functional acceptability severely limit the usefulness of currently available devices. More substantial limits are set by the inability to transfer tactile information, in synthetic form, to the afferent neural system and by the impractical use of sensory substitution channels. As a result most of today's hand prostheses are simple devices made of grippers with one or two degrees of freedom, working under visual control.

Localized force sensors, limiting-force switches and even low resolution tactile sensor arrays have been developed, but at present are little used. Only if current efforts in the development of nerve guidance channels and neural connectors one day prove successful will the use of tactile sensors for hand prostheses be worth reconsideration [60].

Peripheral (limb) neuropathy caused by disease or trauma affects a relatively large fraction of the adult population. Of particular concern in developed countries are the secondary pathologies associated with the loss of peripheral sensation in chronic diabetic patients. The variables to be sensed are the pressure distributions on the foot during standing and walking [61] or the finger and palm contact pressures in object grasping [62]. Practical considerations, however, dictate a rather small number of sensing sites.

Many different transduction techniques and materials with the essential requirements of reliability, robustness, minimum encumbrance and good compliance matching with body tissues [63] have been used.

In the last few years, tactile sensing has begun to be used in functional neuromuscular stimulation (FNS), where orthotic systems have been developed to electrically stimulate paralyzed muscles through feedback from sensors located on the insensate hand or foot [64, 65].

Both single-element compliant pressure sensors and arrays of tactile sensors based on capacitance effects have been developed, but they do not yet satisfy the strict specifications dictated by this particular application in terms of mechanical compatibility, reliability and patient acceptance.

The search for more appropriate tactile sensors in this area of application, however, is actively pursued, the available technology still being at a quite primitive level.

5.2. Haptics in Teleoperators and Telepresence Systems

Teleoperation and telepresence enable humans to extend their manipulative ability or project their active presence to remote locations [66].

More properly, teleoperation means "doing work at a distance," although the term "work" can mean nearly everything. What the term "distance" means is also vague: it can refer to a physical distance, where the operator can remotely act, but it can also refer to a change in scale, where for example a surgeon may use micro-manipulator technology to perform surgery at microscopic level.

Teleoperators definitely need an expansion of their functional performance with respect to the ability to perceive haptic information and to convey it to a human operator in order to fully benefit his sensory-motor skill and decision-making capability.

Teleoperation and telepresence, indeed, necessarily imply a strict interaction between human operator and machine. Increasing demands of superior performance for currently available teleoperators, usually provided only with vision feedback, and for advanced computer interfaces [67] motivate efforts to find new methods and techniques to convey kinaesthetic information through man-machine interfaces.

There are many definitions proposed to describe what "telepresence" means. Telepresence technology "enables people to feel as if they are actually present in a different place or time." [68], or more extensively "enables objects from a different place to feel as if they are actually present" [69, 70].

Very similar to virtual reality, in which we strive to achieve the illusion of presence within a computer simulation, telepresence strives to achieve the illusion of presence at a remote location. The end results of both telepresence and virtual reality are essentially the same, a human-computer interface which allows a user to take advantage of natural human abilities when interacting with an environment other than the direct surroundings [71].

Draper et al. [72] identified three types of telepresence in the literature: simple telepresence, cybernetic telepresence, and experiential telepresence. In the simple definition, telepresence refers to the ability to operate in a remote world. This can be thought of as simple controlling a remote machine. In the cybernetic definition, telepresence is an index of the quality of a human computer interaction. This means telepresence is enhanced by examining the behavioral and physiological performance capabilities and limitations of the human operator. In the experiential definition, telepresence means a mental state in which a user feels physically present within the remote world.

5.3. Robotic Tactile Sensing

The development of robots capable of operating in an unstructured environment or intended to substitute for man in hazardous or inaccessible locations demands the implementation of more sophisticated sensory capabilities, far beyond those available today.

Harmon [73] followed up a survey on automated tactile sensing among developers and potential users, providing a general view of needs and requirements in several areas of application. The analysis of Harmon has also generated tentative specifications for tactile which are still widely referenced by operators in the field.

It should be clear, however, that the exact requirements of a particular sensor depend on its specific use [59].

To perform object manipulation using dexterous end-effectors, the force and motion states of grasped object and finger links should be controlled, possibly using a minimum set of sensors capable of determining in real time the location, orientation and type of contact. This problem has been approached by using resultant force and moment miniature sensors located inside the fingertips of the end-effector to provide the robot with a sense that is more analogous to human kinaesthetic senses. The integration of skin-like and kinaesthetic-like sensing will definitely lead to new robotic systems equipped with artificial haptic perception.

Indeed the quality and quantity of information required to properly command a dexterous robotic end-effector very much depend on the tasks and goals intended to perform.

Sensorial needs of a haptic nature, allowing robotic multi-fingered hands to perform fine manipulative tasks and object exploration, have evolved to the complex set listed below (see Section 4 for more in depth analysis):

(a) monitoring finger coordinates;
(b) measuring point contact forces and torques (resultants);
(c) estimating contact area extension and position;
(d) incipient slip detection;
(e) fine-form discrimination;
(f) probing material bulk properties (hardness, viscoelasticity);
(g) evaluation of surface properties (texture, roughness);
(h) thermal sensing.

Sensing and processing all this information in an integrated system represents a formidable task, overwhelming in its complexity and far beyond our present knowledge and technical capabilities. However, all these sensing modalities have been investigated as isolated tasks and several devices conceived and implemented to show the feasibility of detecting single tactile sensing features.

5.4. Surgical Trainers and Telesurgery

Nowadays, the latest progresses of medicine cannot afford to give up to the benefits of skin-like sensors. Several simulators have been developed for training students in medicine to practice the routine task of inserting a catheter into a patient's vascular system, or more difficult procedures like a colonoscopy or even a lung biopsy. These simulators do not just have to provide vivid computerized visual renderings of human innards, but they also have to convey actual tactile information to the doctor performing injecting, cutting, inserting and palpating tasks [74]. Haptic technology does not just enhance basic medical simulation training, but future applications may even enable doctors to perform surgery over the Internet. As when doctors are interacting with patients, a lot of it is the sense of touch, skin-like sensors play a huge role in providing a realistic medical simulation experience.

One of the most difficult challenges in surgical practice is to change the way surgeons interact with their patients. New technologies, such as virtual reality and robotics, are foreseen to perform accurate telemanipulation tasks revolutionizing the viewpoint to healthcare.

Marescaux et al. [75] reported that surgeons working in New York successfully used remotely controlled robots to remove the gallbladder from a woman in France. This is the world first transoceanic teleoperation on a human-being. Computer-assisted surgery can be applied to a wide variety of applications. A number of operations have been performed using telemanipulation devices, namely, the removal of the gallbladder, prostate, gynaecological tubal reanastomosis, and procedure on the heart, joints and food pipe. Remote and accurate manipulation of instruments is now possible even thanks to the high sensitivity of tactile sensors.

Surgical trainers and telesurgery are fields of application where virtual reality is capable of delivering effective training and assessment systems. Several systems of virtual reality training systems and simulators have been developed offering repeatable, logged and computerized training.

Surgical trainers have been reported in particular in minimally invasive surgery, where the intra-abdominal environment is translated into quite simple, real-time 3D computer graphics that accurately represent the movements of the instruments within a virtual operating volume. Telesurgery opens up new valuable avenues for providing broad and easy access to medical expertises without traveling and is, therefore, time saving for experts and patients. Experimental studies have confirmed the feasibility of robotically assisted operations and the results are comparable to those of conventional techniques. Although much more research has to be done in order to overcome the current limitations, the telemedicine has been increasingly maturing and growing up.

5.5. Posture and Gesture Recognition

5.5.1. Flat Arrays for Posture

Posture recognition implies to detect many parameters such as contact location, object shape, and actual map of pressure distribution.

Typical applications range from footwear and orthotic manufacturering [76] to tire design, from biometrics to ubiquitous computing in smart objects (see Fig. 2).

Flat sensor arrays can be specially designed to be inserted in the sole in order to display real-time static and dynamic pressure distribution. This information can be fruitfully used for improving the shoe's comfort or the technical skill of an athlete, diagnose diabetic ulcers or identify potential health problems associated with the use of shoes with high heels

An emerging application is the measurement of static and dynamic tire footprint pressure distribution patterns to set up the suspension of race vehicles.

Moreover, flexible flat sensors can be used for improving safety for humans. Indeed, these sensors can be used to measure impact force and duration in applications where localized high pressure can often cause the most damage and injury.

Biometrics applications involve the recognition of hand geometry to authenticate the subject identity. The length, width and surface area of the palm and fingers can be extracted from the pressure image of the hand and then used to create a template for each user during an initial registration process.

Finally, flat sensor arrays can find a useful application in car industry to measure the distribution of pressure on the seat when the driver is sitting down. This application can aim at detecting the weight and size of the passenger in order to control the opening of the airbag, to improve the comfort and ergonomics of seats. In the first case, it would be possible to discriminate different profiles and distinguish, for example, a child from an adult and tune the inflation rate of the airbag, accordingly.

Among flat array sensors, it is worthwhile noting conductive polymer pressure sensors (FSRs) manufactured by Interlink Electronics Inc and capacitive sensor technology used by Novel GmbH for pressure distribution measurement systems widely employed in the medical and industrial communities. In particular Novel GmbH provides pressure platforms for functional foot diagnostics, evaluation of treatment and rehabilitation progress, biomechanical and orthopaedic research, in-shoe system for investigating the foot and footwear interface and evaluation of treatment and rehabilitation progress and pressure system for investigating contact pressure with flexible and elastic mats at a variety of interfaces including seats, horse saddles, hands and prostheses.

5.5.2. Wearable Systems for Body Segment Tracking

Biological kinaesthesia and haptics detect mechanical events largely relying on the activity of the subject. Their inherent bidirectional nature implies sensing depends on peripheral receptors, but it is not confined to them. Artificial

Figure 2. Typical applications of flat arrays for posture. On the left side a display of pressure on a car seat is reported, in the middle a foot pressure distribution is shown and on the right side a pressure map of the hand is also shown.

human-like kinaesthetic systems should be able to adequately embed artificial signals referable to the joints possibly in a structured map of local inputs from a number of individual joints. Presently, however, human movement tracking systems generate only real-time data capable to sample body kinematics.

Movement of an object is relative to a point of reference. A sensor attached to the object (i.e., a bodypart) can sense (measure the position and/or orientation of) a source located at the reference or sensor attached to the reference can sense a source located at the object. Sources can be natural or artificial. Referring to sensor(s) and source(s) location, a proposed taxonomy [77] of movement tracking systems in humans follows:

(a) inside-in systems, where sensor and source are both located on body;
(b) inside-out systems, where sensors located on body sense an external source;
(c) outside-in systems, where external sensors sense a source on the body.

In a tracking system the components are in general sensor(s), source(s), interface-electronics, computer, rough data and data treatment algorithms, software for body kinematics reconstruction.

Most of wearable systems for body segments tracking are usually very cumbersome, less handy and less comfortable for the subject. Mainly, the approach to capture body motion and infer human body segment tracking is based on optical sensors strategically placed upon anatomical bony landmarks in the field-of-view from video cameras. Besides photogrammetric methodology, it is possible to track the trajectories of body segments by means of position sensors or sensorized fabric allows capturing body motion of subjects wearing just a usual garment. The fabrication of sensing systems onto substrates which are not only flexible, but also conformable to the human body represents a break-through in many areas of application such as virtual reality, teleoperation, telepresence, ergonomics and rehabilitation engineering. The possibility to realize sensing textiles by coating traditional fabrics with smart materials (piezoresistive, piezoelectric and piezocapacitive polymers) is quite recent and has opened up means of implementing a new type of man-machine interface technology [81].

Gough et al. [78] proposed a sensing garment for body position sensing designed as an adjustable "skeleton" suit. Bickerton [79] described a garment including fabric stretch sensors. Steel, Wallace et al. [80] proposed an intelligent knee sleeve capable of providing immediate audible feedback to the wearer when knee flexion angle during human movement falls into a dangerous range.

Peculiar features that require the application of new processing approaches have then emerged. Having a set of sensors distributed on a garment poses a certain number of new problems, amongst others, the need of minimizing the wiring required to extract the signals from every single sensor. Secondly, given the variability between individuals, the sensors on a garment cannot in general be positioned always exactly at the same location, therefore the repeatability of measurements is not guaranteed on the same subject, and becomes entirely different going from a subject to another. An even more demanding requirement resides in the need for a high immunity to motion artefacts and for provisions to deal with the sensors cross-talk.

Lorussi et al. [82] described a redundant fabric-based system for reconstruction of body posture. This work is based on the observation that a redundant number of sensors distributed on a surface can provide enough positional information to infer the essential features concerning the posture of a subject also loosening the constraint of precise sensor location. This approach borrows from the biological paradigm. A method was presented allowing to operate with large sets of sensors positioned on garments without dramatically increasing the number of reading channels. Various connection topologies have been analyzed and an algorithm for acquisition has been described (for more details see Section 7.1. From an abstract point of view, these sets of sensing fabrics patches linked in different topological networks can be regarded as a spatially distributed sensing field. By simultaneously comparing the sensing field with the value of the joints variables in the identification phase, it is possible to reconstruct postures in the data acquisition phase. The analysis exposed guarantees that all the information needed for the reconstruction can be effectively gathered. It also provides a key understanding of the single sensor influence as well as strategies for density and location of the sensors. Additionally, a reconstruction (inversion) technique based on an identification phase of the entire system has been proposed in the scope of a synthetic and real time data processing, to avoid passing through the sensor space and consider all the sensors as a unique entity to be read and interpreted. This has the further advantage to make the hardware applicable regardless of the specific body structure. Although at preliminary stage this techniques already provides satisfactory results.

5.6. Large Area Force Sensor Arrays in Ambient Intelligence

The use of embedded systems, where computer-based intelligence is integrated into objects with which human beings can interact, is becoming increasingly widespread. This facilitates the creation of ambient intelligence [84]. This exchange of information between objects and environments and humans can closely affect and modify habits, personality, mood or behavior. Skin-like sensor arrays are expected to be an integral part of potential applications in ambient intelligence [85].

Integrating flat sensor arrays in the floor, for example, makes it possible to realize a smart structure able to discriminate people by analyzing their footstep force profile. Moreover, a sensorized floor could provide helpful information within a smart home, where subjects could interact with surrounding environments and modify local preferences such as ambient light, music, temperature according to their needs, merely stepping on the floor. Similar application could find place in the field of smart marketing, where preference could be monitored and controlled the shopping style of consumers. By analyzing the people's weight, shoe size and dynamics of their motion within a shop store, it is possible to gather information on consumers needs and modify the organization of the shop store to optimize it, for example maximizing the product's appeal to different ages or protecting kids from exposure to an inappropriate advertising content.

Also, many applications based on virtual reality and computer games could fruitfully benefit from the use of smart skin sensors. Indeed, they can be easily placed on users interacting with virtual environments and acquire information on position and motion of the body.

Furthermore, a smart skin sensor is thought to be used for covering a human body for recording the area, intensity and duration of body stresses or impacts developed during sport activities (e.g., rugby), work (e.g., acceleration-induced stresses on pilots) or accident situations (e.g., car crashes). This information could be exploited in improving properties of clothing, and make materials more protective and stress absorbing.

6. TRANSDUCTION PRINCIPLES AND MATERIALS

The wide variety of configurations and design options adopted in tactile sensing technology originates from the exploitation of many different transduction effects and materials capable of mechano-electric, mechanomagnetic and mechano-optic conversion. Thermal effects also deserve consideration in this context because of their use in thermal sensing and their unavoidable interference in mechanical sensing.

In Table 1(a) synoptic illustration of intrinsic effects is given with reference to the field of tactile sensing.

In Table 2 indirect (geometric) sensing effects used in tactile sensing are illustrated with reference to the most significant advances.

Due to the very specific nature of tactile sensing, some of the traditional figures of merit in mechanical sensing [86] are rendered insufficient or inappropriate.

Possibly the most peculiar requirements of truly "skin-like" sensing consist in the mechanical compliance of the transducer itself, for increased grasp stability, its conformability to curved shapes and the possibility of realizing high-density miniature sensing arrays.

Not surprisingly, plastics, rubbers and carbon fibers have found widespread use in tactile sensor technology because of their high mechanical compliance and robustness, combined with their ability to be processed into complex shapes. Some polymers and plastic composites also possess intrinsic transduction properties (piezoresistivity, piezoelectricity, photoelasticity, magnetoelasticity, etc.) which render these materials particularly attractive for tactile sensing.

Table 1

Effect	Coupled parameters	Representative materials	Pros	Cons	Typical designs
Piezoresistive	Strain-electrical resistance	Silicon	Compatibility with VLSI	Rigid and fragile	Sugiyama et al. (1990) [93]
		Carbon fibers	Simple and inexpensive	Noisy, scarce reproducibility	Robertson and Walkden (1986) [94]
		Conducting composites Fabrics	Intrinsic compliance, easy fabrication	Hysteresis, low sensitivity	Raibert and Tanner (1982) [95] De Rossi et al. (2002) [126]
		Organic field-effect transistors	Flexible, light, easy integration	Unreliability	Loo et al. (2002) [96]
Thermoresistive	Temperature-electrical resistance	Sintered ceramic thermistors	High sensitivity	Non-linear response	Russel (1985) [57]
Ferroelectric: Piezo	Strain (stress)-polarization	Ferrroelectric polymers (PVDF, P(VDF-TrFE))	High dynamic range, good mechanical properties	Lack of DC response	Dario et al. (1984) [97]
Ferroelectric: Pyro	Temperature-polarization	Ferroelectric polymers (PVDF, P(VDF-TrFE))	Stress components selectively sensed, broad frequency response	Thermal and mechanical effects are difficult to separate	Petterson and Nevill (1986) [98]
Thermoelectric	Temperature-electric potential	Metal thermocouples	Easy patterning	Relatively low sensitivity	Russel (1984) [56]
Electrokinetic	Strain rate-electric potential difference	Charged polymer gels	Easy to match compliance of body tissues	Noisy, inherently dynamic	De Rossi et al. (1988) [99] Sawa et al. (1998)
Magnetoelastic	Strain-magnetic moment	Amorphous ferromagnetic alloys, metallic glasses	Stress component selectivity is possible, good linearity, low hysteresis	Construction of dense arrays is difficult	Luo et al. (1984) [100] Mitchell and Vranish (1985) [101]
Photoelastic	Stress-optical birefringence	Photoelastic polymers (polyurethanes, epoxy resins, acrylic resins)	No electrical interference	Narrow dynamic range, construction of dense array is difficult	Jacobsen et al. (1984) [102]

Table 2

Geometric change in	Coupled parameters	Working principles	Pros	Cons	Typical designs
Capacitance	Force-voltage (or frequency)	Compressive force reduces thickness of a dielectric, increasing capacitance	Large dynamic range high spatial resolution, good frequency response, compatible with VLSI technology	Noise susceptibility	Chun and Wise (1984) [103] Fearing et al. (1986) [32] Guerrieri (2002) [127]
Resistive contact	Force-voltage drop	Contact resistance of conducting elastomers changes upon squeezing	Simple construction, compatible with VLSI technology, high spatial resolution	Some hysteresis, only normal force detected	Raibert (1984) [104]
Inductance	Displacement-induced voltage	A moving core, energized by a drive coil, induces voltage in a sense coil	Very large dynamic range	Poor reliability, bulky, low spatial resolution	Sato et al. (1986) [105]
Magnetic flux	Force-voltage	Contact-force-induced displacements change magnetic flux detected by magnetoresistive or Hall effect transducers	Large dynamic range, robustness, high frequency response, stress component selectivity possible	Noise susceptibility, scarcely investigated	Hackwood et al. (1983) [117] Kinoshita et al. (1983) [106] Vranish (1986) [107]
Ultrasonic time of flight	Force-ultrasonic pulse delay	Force causes a rubber layer to deform and US propagation time to vary accordingly	—	Non linear response, complex circuitry, high hysteresis	Shoemberg et al. (1983) [108]
Optical transmittance	Force-light intensity	Through displacement of light-pass occluders	Reliability	Bulcky	Rebman and Morris (1984) [109] Maalej and Webster (1988) [110]
Optical reflectance	Force-light intensity	Deflection of reflecting elements changes intensity of reflected light	Good spatial resolution, immunity from EMI	Narrow dynamic range, difficult calibration	Bejczy (1981) [111] Schneiter and Sheridan (1984) [112]
Optical coupling	Force-light intensity	Totally internally reflected light is modulated by compliant, grooved pad	High spatial resolution, good frequency response, immunity from EMI	Difficult calibration, only normal force detected	Tanie et al. (1985) [113] Begej (1988) [114]

Reviews on tactile hardware [87–90] are available for the interested reader and tactile sensor materials and design issues are also discussed extensively in a book edited by Webster [91].

Moreover, a broad survey of the technology supporting general purpose manipulation has been published by Grupen et al. [92], providing useful information on dexterous end-effectors and tactile sensing.

7. DEVICES AND SYSTEMS

Skin-like sensor usually consists of an array of touch sensitive sites, which may be capable of measuring more than one property. The contact forces measured by a sensor are able to convey a large amount of information about the contact. Texture, slip, impact and other contact conditions generate force and position signatures, which can be used to identify the state of mechanical interaction.

Many physical principles have been exploited in the development of tactile sensors. Here we report a survey of skin-like sensor arrays on the basis of the technology involved. The use of compliant materials that have defined force-resistance characteristics have received considerable attention in touch and tactile sensor research. The basic principle of this type of sensor is the measurement of the resistance of a conductive elastomer or foam between two points. Most of the sensors use an elastomer that consists of a carbon loaded rubber. The resistance of the elastomer changes with the application of force, resulting from the deformation of the elastomer altering the particle density.

This technology enables the implementation of high density arrays, able to construct a tactile image of good resolution.

The conductive elastomer or foam based sensor, while relatively simple, does suffer from a number of significant disadvantages related to long time constant and nonlinear force–resistance characteristic. In addition, the elastomer becomes permanently deformed after repeated loading, giving to the sensor a poor long-term stability and requiring replacement after an extended period of use.

Nevertheless, most of tactile sensors are based on the principle of resistive sensing. This is due to the simplicity of their design and interface to the processing unit.

Tekscan Inc. produces a range of sensing systems including pressure mats, in-shoe foot pressure arrays, and other gait and stance measuring systems. The sensing principle is based on arrays of resistive elements embedded in a large area flexible film only 0.18 mm thick. This system allows the flexible sheet to be cut to shape and inserted into shoes for real-time pressure measurements (see Fig. 3).

Tekscan technology provides pressure measurement system is an extremely thin (0.1 mm), flexible tactile force sensor. Sensors come in both grid-based and single load cell configurations, and are available in a wide range of shapes, sizes and spatial resolutions (sensor spacing). These sensors are capable of measuring pressures ranging from 0–15 kPa to 0–175 MPa. Moreover, Tekscan provides high resolution matrix-based products. Sensing locations within a matrix can be as small as 0.140 mm^2; therefore, a one square centimeter area can contain an array of 170 of these locations. The standard sensor consists of two thin, flexible polyester sheets which have electrically conductive electrodes deposited in varying patterns. The inside surface of one sheet forms a row pattern while the inner surface of the other employs a column pattern. The spacing between the rows and columns varies according to sensor application and can be as small as $\sim$0.5 mm.

Before assembly, a propretary, thin semi-conductive coating (ink) is applied as an intermediate layer between the electrical contacts (rows and columns). This ink provides the electrical resistance change at each of the intersecting points.

When the two polyester sheets are placed on top of each other, a grid pattern is formed, creating a sensing location at each intersection. By measuring the changes in current flow at each intersection point, the applied force distribution pattern can be measured and displayed on the computer screen.

Based on the same principle of changing the electrical resistance upon mechanical solicitation is the strain gauge. When attached to a surface it detects the change in size of the material as it is subjected to external forces. Strain gauges are manufactured by either resistive elements (foil, wire, or resistive ink) or from semiconducting material. A typical resistive gauge consists of the resistive grid being bonded to an epoxy backing film. If the strain gauge is prestressed prior to the application of the backing medium, it is possible to measure both tensile and compressive stresses. The semi-conducting strain gauge is fabricated from a suitable doped piece of silicone; in this case the mechanism used for the resistance change is the piezoresistive effect.

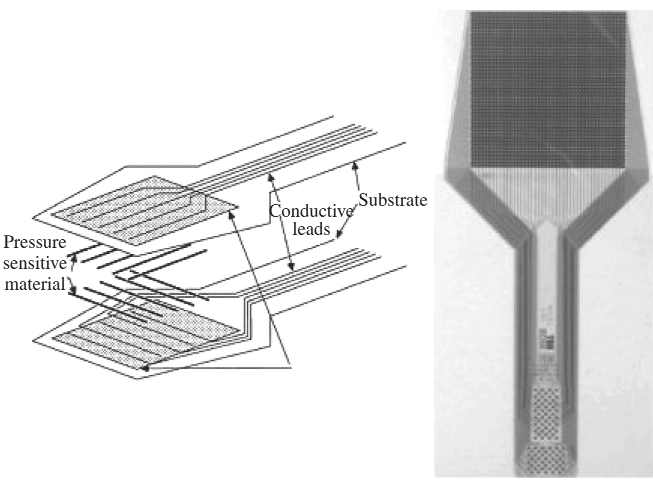

Figure 3. Flexible, thin-film contact resistive force and pressure sensors printed on polyester substrates manufactured by Tekscan Inc. (Reprinted with permission from [85], T. V. Papakostas et al., in "Proceedings of the 1st IEEE Sensors Conference," Vol. 2, p. 1620. Orlando, FL, 2002. © 2002, IEEE.)

When applied to touch applications, the strain gauge is normally used in two configurations: as a load cell, where the stress is measured directly at the point of contact, or as a strain sensor placed onto the structure whose deformation has to be monitored.

Brock and Chiu [104] have designed and constructed a tactile sensor based on these premises using 16 semiconductor strain-gauges mounted onto the structural support of the terminal phalanx of an artificial finger. The strain-gauges are bonded onto the four legs of a steel Maltese cross and the contact wrench system is calculated by inverting a redundant linear equation system in which strain readings, geometrical factors and material elastic coefficients are known entities.

Many of new tactile devices are based on thin polymeric film which can behave as piezoresistivive or piezoelectric sensors. Piezoresistive sensors changes resistance in a predictable manner following application of force to its surface. It is normally supplied as a polymer sheet which has had the sensing film applied by screen printing. The sensing film consists of both electrically conducting and non-conducting particles suspended in matrix. Microsized particles are formulated to reduce the temperature dependence, improve mechanical properties and increase surface durability. When a force is applied to the surface of a sensing film particles are brought into contact to the conducting electrodes, changing the resistance of the film.

A notable commercial device is the FSR (Force Sensing Resistors). These are resistive polymer film elements manufactured by Interlink Electronics Inc and are widely used in pointing and position sensing devices such as joysticks. Since 1985, Interlink Electronics has pioneered the development and manufacture of patented Force Sensing Resistors for mission-critical medical, automotive, and military applications [116].

Polymeric materials can also exhibit *piezoelectric properties* such as polyvinylidene fluoride (PVDF).

Polyvinylidene fluoride is not piezoelectric in its raw state, but can be made piezoelectric by heating under an electric field. Polyvinylidene fluoride is supplied in sheets between 5 microns and 2 mm thick, and has good mechanical properties. A thin layer of metallization is applied to both sides of the sheet to collect the charge and permit electrical connections being made. In addition, it can be moulded, hence PVDF has number of attraction when considering tactile sensor material as an artificial skin.

Another class of tactile devices is based on *magnetic transduction*. These devices are based on the measurement of a change of magnetic flux density when a small magnet is moved by an external force.

The flux measurement can be made by either exploiting the Hall effect or by a magnetoresistive device.

Alternatively, a magnetoelastic core of a transformer can be deformed by an external pressure producing a change in the magnetic coupling between transformer windings, or in the coil inductance. Both types of sensors exhibit advantages of having high sensitivity and dynamic range, a linear response, and physical robustness.

Hackwood et al. [117] proposed the use of an array of magnetic dipoles, embedded into an elastic pad, whose position and orientation can be detected by magnetoresistive elements. Sensing normal and tangential contact forces as well as torque was implied to be possible. Although the primary motivation for its development was fine-form discrimination for object shape recognition (see Section 4.3), the sensor was also intended to be used in detecting surface tractions and 'stickslip' region dynamics before gross relative motion occurs. Work along similar lines has been reported by Novak [118], in which a preliminary analysis and design of a capacitive sensor array, potentially capable of tensorial strain detection, is given.

The rapid expansion of *optical technology* in recent years has led to the development of a wide range of tactile sensors. The operating principles of optical-based sensors can be intrinsic, where the optical phase, intensity, or polarization of transmitted light are modulated without interrupting the optical path, and extrinsic, where the physical stimulus interacts with the light external to the primary light path.

Intrinsic and extrinsic optical sensors can be used for touch, torque, and force sensing. In touch and force-sensing applications, the extrinsic sensor based on intensity measurement is the most widely used due to its simplicity of construction and the subsequent information processing. Optical sensors have many benefits. They are immune from external electromagnetic interference, intrinsically safe, very small in size and weight. Moreover the use of optical fiber allows the sensor to be located at some distance from the optical source and receiver. Tactile optical sensors can be realized modulating the intensity of light by moving an obstruction into the light path or exploiting the property of photoelasticity where stress or strain causes birefringence in optically transparent materials. In photoelasticity phenomenon light is passed through the photoelastic medium. As the medium is stressed, the photoelastic medium effectively rotates the plane of polarization and hence the intensity of the light at the detector changes as a function of the applied force. This type of sensor is of considerable importance in the measurement of slip [119].

Optical fibers where originally used solely for the transmission of light to and from the sensor, however tactile sensors can be realized by using the fiber itself. A number of tactile sensors have been developed using this approach, usually based on internal-state microbending of optical fibers [120, 121].

Technologies for micromachining sensors are currently becoming widespread. The developments can be directly linked to the advanced processing capabilities of the integrated circuit industry, which has developed fabrication techniques that allow the interfacing of the non-electronic environment to be integrated through micro-electromechanical systems.

The excellent characteristics of silicon, that has made micromachined sensors possible, include a tensile strength comparable to steel, elastic to breaking point, low mechanical hysteresis in devices made from as single crystal, and low thermal coefficient of expansion.

Most of MEMS (Micro-Electro-Mechanical Systems) based sensor rely on the development of advanced silicon pressure sensors and silicon accelerometers. These efforts are primarily driven by existing and potential high-volume applications in automotive, medical, commercial, and consumer products. The most important requirements are typically for moderate performance at very low cost. Many pressure sensors and accelerometers with significant levels of electronic integration are under development or even in production. Jiang et al. [122] have developed a new microfabrication technology that enables the integration of MEMS devices on a flexible polyimide skin. The flexible skin consists of many individual silicon islands connected together by a thin polyimide film (see Fig. 4). Engel et al. [123] reported a multi-modal, flexible, and robust tactile sensing skin based on polymer substrates.

Researchers from the University of Tokyo [96] have devised pressure-sensor arrays built from inexpensive organic, or plastic, transistors on a flexible material. This

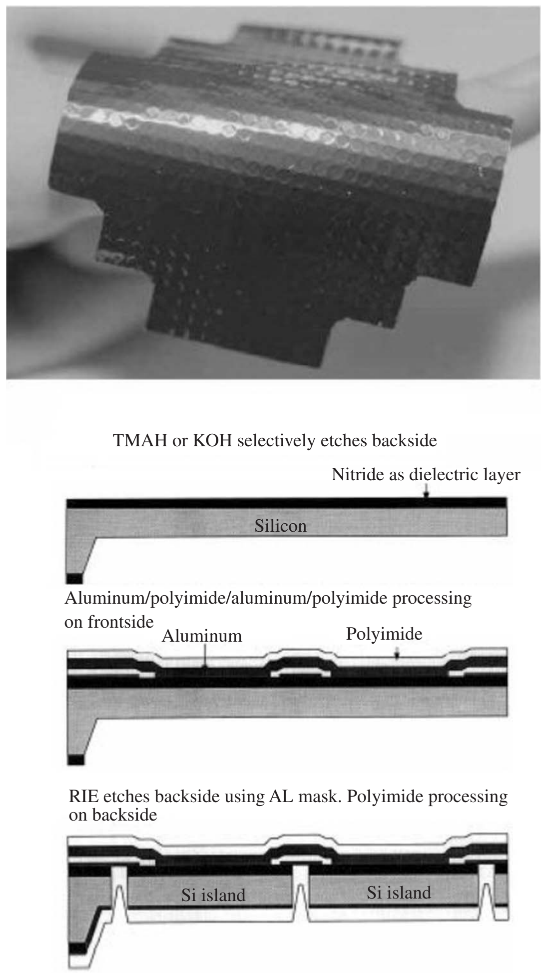

Figure 4. Wafer-size flexible skin based on MEMS technology. (Reprinted with permission from [122], F. Jiang et al., *Sensor. Actuat. A—Phys.* 79, 194 (2000). © 2000, Elsevier.)

allows for dense arrays that can be used over large areas. The arrays could be used in pressure-sensitive coverings in artificial skin that would give robots the means to interact more sensitively with their surroundings. The first prototype of sensor skin is an eight-centimeters-square sheet containing a 32-by-32 array of organic sensors. The great disadvantage of the pressure-sensitive skin is still the reliability. The electrical characteristics of organic transistors, indeed, change in a matter of days.

Beebe et al. [124] describe a silicon-based piezoresistive force sensor that addresses the problems of robust packaging, small size and overload tolerance.

In last few years, a new technology based on sensing fabrics is emerging. The fabrication of sensors onto substrates which are not only flexible, indeed, but also conformable to the human body is increasingly becoming widespread. Smart textile area, indeed, has undergone a great development leading to wearable sensing systems (see Fig. 5). Truly wearable instrumented garments capable of recording kinematic variables are crucial for several fields of application, from multi-media to rehabilitation and sport medicine.

The transduction properties can be realized either exploiting the intrinsic electromechanical properties of special threads made of conducting elastomer or coating traditional fabrics with smart materials (piezoresistive, piezoelectric and piezocapacitive polymers).

By using commercial embroidery processes, it is possible to stitch sensing surfaces and conductive threads defining a matrix pattern [125]. Alternative methods consist in using screen printing technologies, in which strain sensors, e.g., carbon filled rubber based sensors, are applied in according to predetermined masks. In particular, the textile substrate can be functionalized by means of different techniques. Here we report two technologies. The first one is based on using a conductive mixture, commonly carbon filled silicone rubber, smeared over a piece of fabric previously covered by an adhesive mask cut by a laser milling machine according to the shape desired for the sensors. This treatment confers to the fabric piezoresistive properties [82, 83, 126]. The latter technique includes a distributed passive array of capacitors, whose capacitance depends on the pressure exerted on the textile surface. Capacitors can be made by coupling capacitance between two fabric conductive strips separated by an elastic and dielectric material. The sensing array results from the crossing of these conductive threads patterned in rows and columns of a matrix. When the dielectric layer between a given row and column of electrodes is squeezed, as pressure is exerted over the corresponding fabric area, the coupling capacitance between the two is increased. By scanning each column and row the image of the pressure field can be obtained [127].

In the last few years, textile technology progressed toward a design philosophy of integrating embedded computation and sensing into usual garments.

Finally, a new typology of smart sensors where a complete sensing system rather than individual sensors, together with individual interfaces and interconnections have been developed. This permits the signal processing to be brought as close as possible to the sensor or integrated with the sensor itself. The significant feature of smart sensors is that the substrate incorporates VLSI circuitry so that each sensing element not only measures data but processes them as well. Each site performs the measurements and processing operations in parallel. The main difficulty to date with this

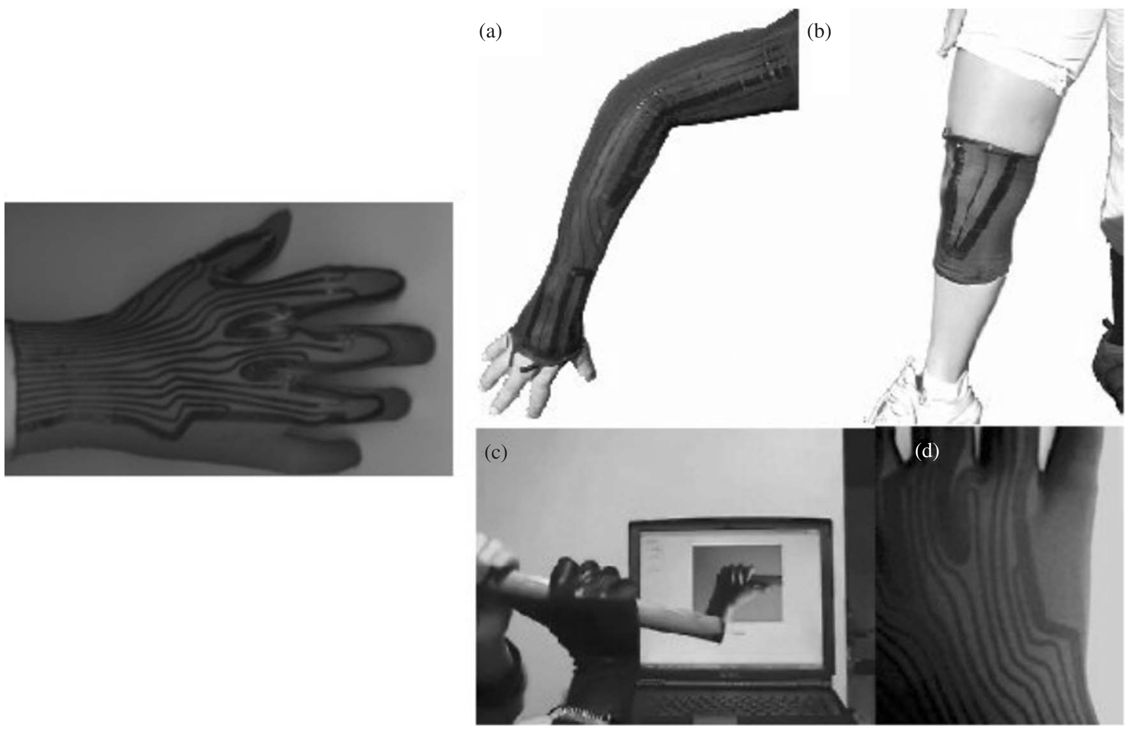

Figure 5. Truly wearable systems based on sensorized fabric. (Reprinted with permission from [82], F. Lorussi et al., *IEEE Sens. J.* 4, 807 (2004). © 2004, IEEE.)

approach is poor discrimination and susceptibility to physical damage However, the VLSI approach was demonstrated to be viable, and alleviated the problems of wiring up each site and processing the data serially.

7.1. Reading Sensor Arrays

Sensor arrays may be endowed with a large number of sensors allowing to gather redundant information even if every single reading is not extremely accurate. This leads to a great versatility in device realization. Single sensor reading increases the complexity of the electronic acquisition system dramatically. In order to address this problem, several topologies of sensor interconnections to reduce the number of sampling channels and tracks can be envisioned. Each sensor can be represented as a bipolar device. Possible strategies consist in connecting arrays of sensors in series, parallel networks or simply connecting each sensor to the four neighboring ones to form a net of quadruples (see Fig. 6). The first two configurations are topologically dual. Pairs of sensors (whose distance is negligible with respect to the geometric dimension of the net) are connected rows by columns. The inevitable crossing of wires makes it necessary to electrically insulate them to realize series and parallel connections.

By reading a variation of a column and of a row, it is possible to identify a precise point in the net. To do this it is necessary to assume that sensor variation occurs at any one time. With respect to a single sensor reading, these two topologies are advantageous (reduced the number of channels) if $N \geq 6$, even if they lead to a loss in the accuracy of signal reconstruction. Even though the series network exhibits the better sensitivity and accuracy both topologies have several limitations due to the strong condition that sensors variations occur at any one time, in order to univocally determine the point in the network in which sensor response changes. An alternative strategy, usually used in acquisition system based on matrix configuration, is to introduce some logical circuitry in order to sequentially scan each channel [128]. By using suitable digital switches, indeed, it would be possible to read the signals at boundaries of the network but directly addressing the single sensors. However, this configuration involves a careful scanning timing as well as a supplementary hardware to place onto garments and an increasing of the number of connections.

Another strategy, which however involves a high computational load, is to infer the space varying resistance value on a conductive surface by making only measurements at the surface borders. A very similar problem arises in the field of Electrical Impedance Tomography, where the resistive properties of a body are investigated by applying electrodes on its surface. In the works of Cheney et al. the issue is first described in its continuum formulation, based on Maxwell and constitutive laws; then the discretized version, more physically sound due to the nature of the measuring electrodes, is formally derived [129, 130].

In order to sequentially acquire sensors in a distributed network an electronic multiplexers provide important advantages. Indeed, in case of multiple measurement locations, the costs for each channel can be reduced dramatically by using a multiplexer. It is worthwhile noting that, usually, sensors are represented as an electrical resistance or a capacitance, but reading strategies above described can be, in principle, applied to a generalized impedance. The only difference can consist in using a dedicated electronic circuit in

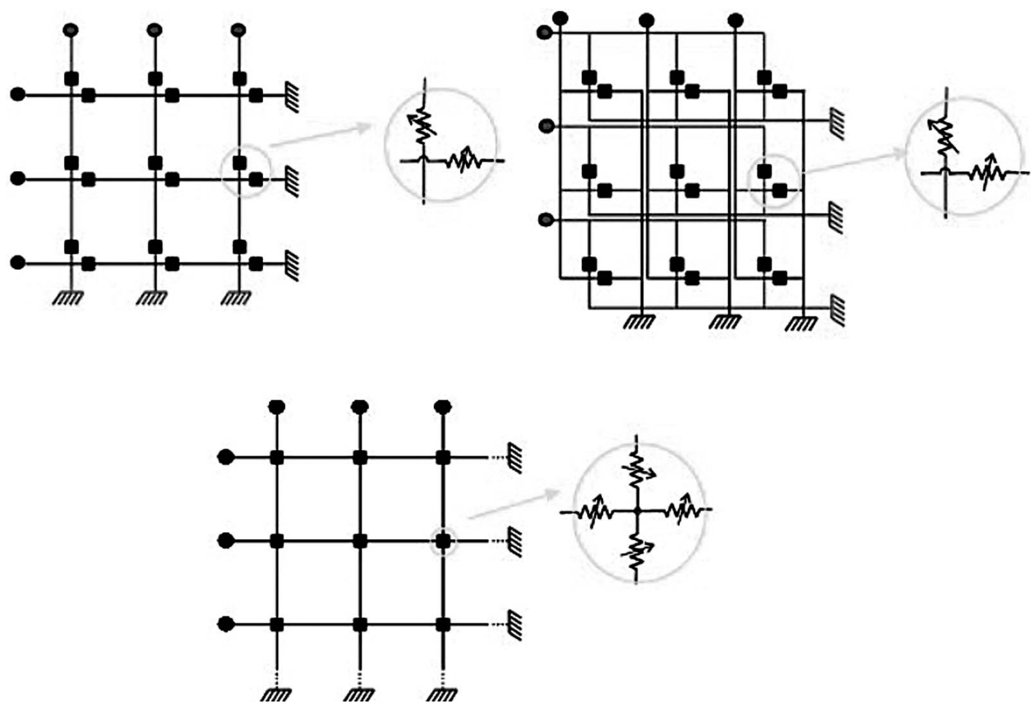

Figure 6. Several topologies used in sensor arrays: connection in series, parallel and net of quadruples. (Reprinted with permission from [83], D. De Rossi et al., "Proc. of IEEE Sensors," p. 1608. Orlando, FL, 2002. © 2002, IEEE.)

relation to the variable to be read (electric charge, voltage, current, continuous or alternating).

8. CONCLUSION

Although the rapid growth in interest in the field of tactile sensing has initiated significant progress, little fall-out in real applications has occurred, and the present market for these devices is still marginal, despite some early optimistic forecasts. Future widespread use of tactile and haptics systems and ambient intelligence is foreseen, but the time scale for these events to occur should be realistically correlated with the great theoretical and technical difficulties associated with these fields and with the economic factors that ultimately drive the pace of their development. More and more bio-inspired approaches are emerging in the area of skin-like sensing also trying to capture the ingenuity of neural processing in terms of features extraction and representation improving the level of machine taction. New artificial systems should necessarily incorporate more knowledge of neural-like processing as advances in machine vision have shown in the last decades.

GLOSSARY

Data glove A glove equipped with sensors able to sense movements of the hand and interfacing them with a computer. Data gloves are widely used in virtual reality environments where the user sees an image of the data glove and can manipulate the movements of the virtual environment using the glove.

End effector In robotics, an end effector is a device or tool connected to the end of a robot arm. The structure of an end effector, and the nature of the programming and hardware that drives it depends on the intended task.

FSR (Force Sensing Resistor) The FSR is a very thin layered device with metal patterns printed on 2 Mylar sheets, with a conductive polymer layer embedded between the 2 sheets. The conductive layer reduces resistance to the flow of electrons as the pressure between the Mylar layers increases.

Haptic interface Force reflecting device which allows a user to touch, feel, manipulate, create, and/or alter simulated D-objects in a virtual environment.

Haptics Field of study where touch (tactile) sensation and control interact with computer applications. By using special input/output devices (haptic interface), users can receive feedback from computer applications in the form of felt sensations in the hand or other parts of the body.

Incipient slip detection Technique aiming at identifying the partial slip occurring on the contact surface when the fingertip is pressed and slid slightly on a rigid plate.

Kinaesthesia The sensory modality subserved by receptors in the capsules of joints and other periarticular mechanoreceptors which allows the organism to sense the position and movement of one part of the body with respect to another.

Mechanoreceptors Cells specialized to transduce mechanical stimuli and relay that information centrally in the nervous system. Mechanoreceptors include hair cells, which mediate hearing and balance, and the various somatosensory receptors, often with non-neural accessory structures.

MEMS (Micro-Electro-Mechanical Systems) Micro-Electro-Mechanical Systems (MEMS) are based on the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology. While the electronic components are fabricated using integrated circuit (IC) process sequences (e.g., CMOS, Bipolar, or BICMOS processes), the micromechanical components are fabricated using compatible “micromachining” processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices.

Neural network In information technology, a neural network is a system of programs and data structures that approximates the operation of the human brain. A neural network usually involves a large number of processors operating in parallel, each with its own small sphere of knowledge and access to data in its local memory. Typically, a neural network is initially trained or fed large amounts of data and rules about data relationships. A program can then tell the network how to behave in response to an external stimulus.

Prosthetics The branch of medicine dealing with the production and use of artificial body parts.

Rapidly adapting receptor A mechanoreceptor that responds quickly to stimulation but that rapidly accommodates and stops firing if the stimulus remains constant. Examples are Meissner’s corpuscles, Pacinian corpuscles, and Golgi-Mazzoni corpuscles.

Rheology Rheology is the study of the deformation and flow of matter. The term rheology was coined by Eugene Bingham, a professor at Lehigh University, in 1920, from a suggestion by Markus Reiner, inspired by the Heraclitus’ famous expression “panta rhei”: everything flows. Rheology has important applications in the engineering sciences and in physiology.

Slowly adapting receptor A mechanoreceptor that responds slowly to stimulation and continues firing as long as the stimulus continues. Examples are Merkel’s disks and Ruffini’s corpuscles.

Somatosensory cortex Area of the parietal lobe concerned with receiving general sensations. It lies posterior to the central sulcus.

Teleoperation The remote manual operation of equipment that is usually not within the direct eyesight of the operator, yet the operator requires and is provided with sensory information (sight, sound, accelerations, etc.) for effective manual control.

Telepresence Technology enabling people to feel as if they are actually present in a different place or time or more extensively enabling objects from a different place to feel as if they are actually present.

Telesurgery Surgical procedures carried out at a distance thanks to advances in robotic and computer technology and their applications to surgery.

Virtual reality An artificial environment created with computer hardware and software and presented to the user in such a way that it appears and feels like a real environment.

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