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A SENSORISED SCENARIO FOR BASIC INVESTIGATION ON ACTIVE TOUCH

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The development of artificial tactile capabilities for advanced robots requires substantial progress in the fields of tactile sensors, end-effectors and control. Studies have been made on simple bionic analogues of the components of the human tactile system, such as an articulated finger equipped with proprioceptive sensors and skin-like tactile sensors, and a static platform simulating the palm. A sensor-based control strategy intended to be a basic approach to future machine tactile perception has been considered in some detail for the finger. Preliminary results on the use of simple tactile exploratory primitives demonstrate the usefulness of the proposed scenario for investigation on active touch.

Research on tactile sensing is receiving increasing attention in advanced robotics. Reasons for this interest can be found primarily in the dramatic improvement that tactile capabilities determine the performance of industrial robots. However, many investigators active in the field of non-industrial advanced robotics are also attracted intellectually by the challenging idea of reproducing human tactile functions in automata.

A number of industrial operations, such as those related to assembly, would benefit from the appropriate use of tactile feedback for manipulator control. But the widest field of applications for robots equipped with tactile sensitivity is the area of non-industrial robotics, where environmental conditions can be unpredictably variable and adaptivity becomes a primary requirement.

The sense of touch in robotics has been studied by modelling features and functions of the human tactile system. There are two basic reasons for such a bionic approach. The first is that the human tactile system demonstrates the effectiveness of tactile information in low- and high-level control schemes. The second reason is that advanced robots are expected to collaborate with, or substitute, humans in situations where a human type of response is

Tactile sensing systems

The notion that tactile sensitivity is a product of the operation of a complex system, rather than of the simple connection of individual devices, is slowly gaining acceptance among robotic investigators[1]. Yet, the central nervous system of evoluted organisms is a clear example of this type of operation.

The human central nervous system is organised as a hierarchy of different sensory motor systems, increasingly interrelated at the higher levels and eventually merged at the cortical level into a unified command and control structure. At the bottom level, the spinal cord includes axon bundles, some carrying sensory signals from the skin, muscles and joints to the brain, others carrying commands from the brain to the motor neurons, and some others carrying information back and forth between computer centres in the grey matter of the cord itself. The first, and best understood, computational level in the sensory motor system is the muscle stretch reflex, a servo system that keeps muscle at constant length despite variation in external load.

The second level of the human central nervous system is the brain stem. At the same level, the cerebellum is particularly involved in sensory motor coordination of rapid and precise muscular activities. Feedback from muscle spindles, Golgi tendon organs and tactile receptors in the skin and joints are managed by the cerebellum.

At the top level of the hierarchy, the forebrain organises sensory feedback and coordinates motor commands according to goal-directed behavioural schemes. An artificial tactile system based on this anthropomorphic model should be provided with sensory and motor organs, along with low-level and high-level processing and control capabilities. Anthropomorphic analogy also indicates that a multifingered, multiple degree-of-freedom hand would be a versatile and efficient end-effector for advanced robots.

The control of an aritificial hand requires various types of sensorial feedback, whose degree of sophistication depends also on the primary hand function. In fact the human hand has both functions of an effective and versatile motor organ and of a very sensitive and accurate sensory receptor.

When grasping and manipulative functions are privileged for carrying out specific tasks (as, for instance, in the industrial assembly of an electrical switch), sensory requirements may be only those needed to obtain a compliant type of control[2]. Hence, the torque and position of joints should be sensed in order to control contact forces along certain directions and to impart the desired movements along other directions. It should be pointed out, however, that the same force and position data necessary for manipulative control are also useful, at superior control levels, to reconstruct the 3-D shape of the manipulated object.

A similar observation holds for true tactile sensors. In fact information on simple contact is useful for the low-level control of manipulation, but the broad range of data on the physical properties of the manipulated object that are provided by the human skin receptors (and that could be provided in a robot by suitable artificial counterparts) are also essential for cognitive purposes, i.e. object recognition.

Tactile perception is a superior function managed directly by the top hierarchies of the central nervous system. Perception requires skilled use of manipulative functions and implies purposive behaviour. In particular, tactile exploration is based on hand and finger movements directed to elicit tactile stimuli that, when properly organised, allow the brain to associate the explored object with an element of a database of existing models, or to construct a new model.

From these considerations a fundamental connection becomes evident between research on advanced tactile sensing in robotics and artificial intelligence. However, as tactile perception is the result of a long evolution of brain functions (and also the final acquisition of complex and demanding learning efforts during childhood), we could expect that the introduction of advanced tactile capabilities in a robot will require an analogous, gradual process.

The first step of this robotic evolution is, almost as in a baby, the learning of some tactile primitives, i.e. the equivalent of a set of grammar rules for object manipulation and exploration. For this purpose, an ideal scenario has been devised to reproduce the features and investigate the operation of an artificial tactile sensing system.

Elements of the scenario

The scenario, illustrated in Fig. 1, includes an anthropomorphic, four degree-of-freedom finger equipped with sensors for proprio- and exteroception, and a sensorised static platform that simulates a second degenerated finger or the palm of an artificial hand.

The choice of a single finger rather than a multifingered hand is justified in this phase of the research by the fact that a finger is easier to control so it is easier to concentrate efforts and computing resources on the extraction of tactile sensorial data and their use. Moreover, this case is still significative, since a number of tactile exploratory acts are performed with a single finger.

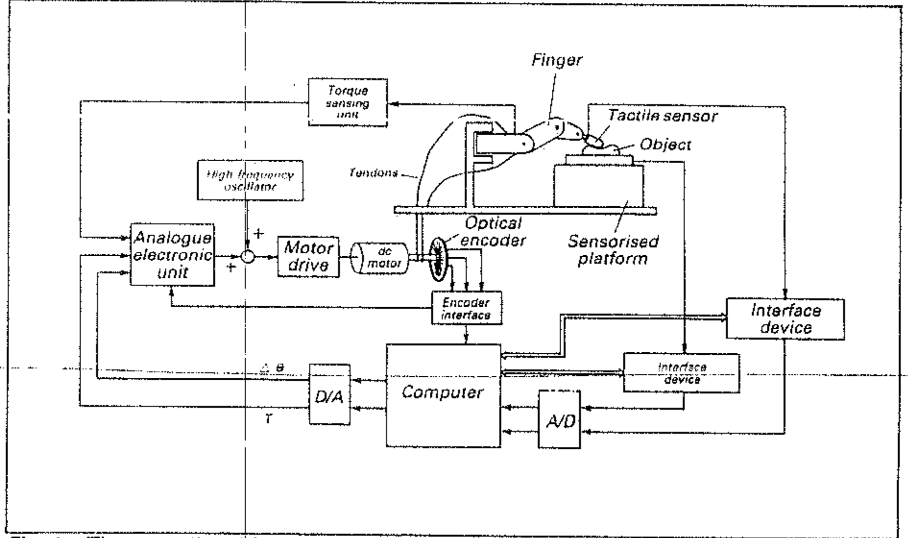


Fig. 1 The overall architecture of the proposed scenario

As effective sensory motor control of the finger is the basic condition for any successive manipulation and exploration, substantial efforts have been devoted to the study of sensor-based finger motion. The same technology has been chosen for the tactile sensors included in the scenario, with the exception of the tendon force proprioceptive sensors, based on conventional strain-gauge techniques.

The reasons for the choice of ferroelectric polymers as transducer materials have been discussed extensively in previous papers[3,4], along with their basic operation principles, working modes and inherent limitations.

Sensorised platform

In the scenario, the object to be explored lies on a multisensor, flat platform that has multiple functions. Since the sensing elements (forming a square matrix of 256 sites in the version being used) are made of the polymer polyvinylidene fluoride (PVF_2) that possesses piezo- and pyroelectric properties, both effects can be exploited to obtain information on the object.

In fact the platform, a section of which is shown in Fig. 2, can be used as a pseudovisual sensor to detect the projection of the object lying on it by exploiting the pyroelectric sensitivity of PVF_2 sensors to impinging infrared radiation[5]. Later, when the exploratory finger presses the object, the PVF_2 sensors provide a piezoelectric response proportional to the forces that the object transmits to the platform.

Two different electronic units have been developed to scan the PVF_2 matrix. In the simplest unit, the charge generated by each sensor is converted in a voltage level by individual high-impedance amplifiers. By comparing voltage levels to a threshold value, it is possible to discriminate the shielded sensors from the others and thus to reconstruct the 'shadow' of the object on the platform. From this information the object position and orientation can be derived using algorithms similar to, but much simpler and faster than, those used in vision[6]. These data can be processed by the control unit in order to command a convenient approaching trajectory to the finger.

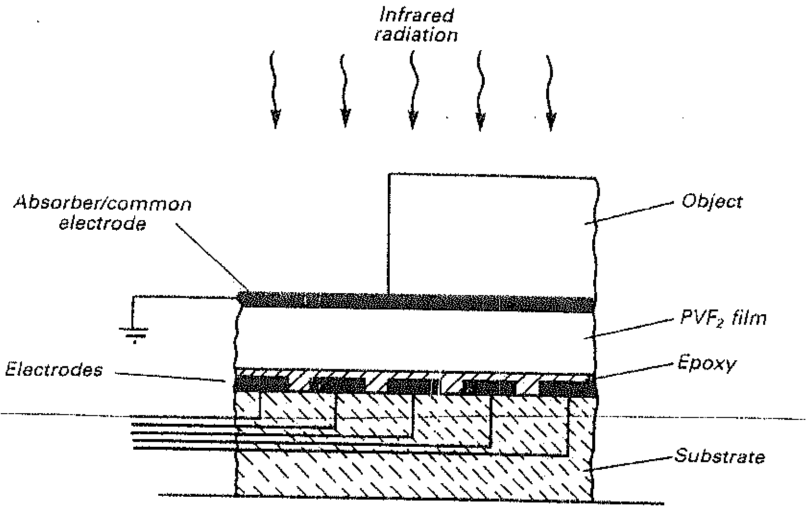


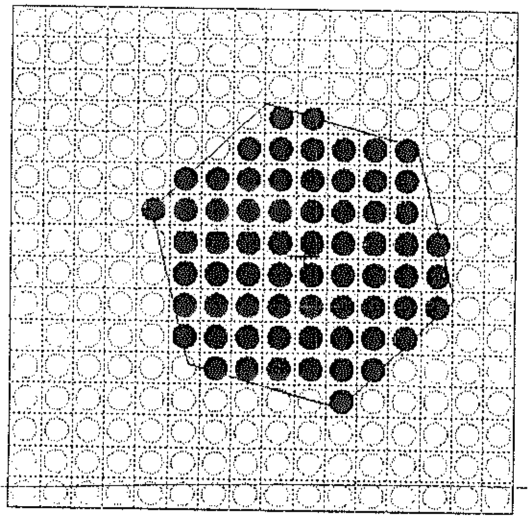
Fig. 2 Cross-section of the sensorised platform

A second electronic unit has been designed to provide continuous, rather than binary, measurement of the signal detected by each PVF_2 sensor. In this unit the charge generated by the PVF_2 sensors is passed through an analogue multiplexer and sequentially sent to a single-charge amplifier[7]. The resulting voltage signal is digitised and processed by the control computer in order to reconstruct the thermal (or pressure) signal waveform acting on the sensor.

This scanning method has a number of analogies with that currently adopted in CCD imagers. An integrated polymer-CCD tactile sensor would actually possess several attractive features.

As anticipated, the platform (in its present configuration or in a possible improved version with different dimensions and denser sensor arrays) can operate functionally either as a degenerated, flat finger or as a sensorised palm. In fact the technology devised for the development of the tactile sensors (a PVF_2 film bonded onto a flat or curved printed circuit board that defines sensor shape, spacing and dimension) allows substantial design freedom.

The first platform developed includes an array of 16 × 16 circular sensing sites, 6mm diameter, and 8mm centre to centre spacing. An example of a pseudovisual image obtained with this platform is depicted in Fig. 3.



Real centre of mass:	73.903	64.785
Recognised centre of mass:	73.970	64.537
Error on recognition of CM:	0.257mm	

Fig. 3 Computer reconstruction of a hexagonal object located on the PVF_2 sensing platform. The actual and calculated coordinates of the centre of mass are also shown

The second platform that has been constructed comprises an array of 8 × 16 circular sensing sites, 1.5mm diameter, 3mm centre to centre spacing, and it was obviously closer to the notion of a degenerated flat finger. Tests performed on each sensor demonstrate that forces as small as 0.01N are measurable with excellent linearity, negligible hysteresis and large bandwidth (from about 0.05Hz to more than 100Hz).

The design of this class of platforms provided interesting hints for analysis. One area that needs further probing is the optimisation of the sensor's number, spacing and disposition; a second area is related to the increasingly evident opportunity of measuring not only normal, but also tangential contact forces on each sensing site[8].

The articulated finger

During object exploration, a finger operates as a tool for bringing and keeping in contact the tactile receptors located in the fingerpad with the surface of the object to be explored. This mode of operation effectively enhances tactile performances by enlarging the explored area through the movements of a small, sensorised surface.

The finger that has been designed and constructed has four degrees of freedom and is actuated by tendons routed through flexible and incompressible sheaths[9]. One dc servomotor imparts the desired torque to each joint via two pretensioned tendons. The position and velocity of the joints are monitored by incremental encoders, while foil strain gauges are use to measure the tension and consequently, the torque of joints.

The cylindrical distal phalanx of the finger supports a PVF_2 composite tactile sensor designed to provide multiple sensorial information.

The primary function of the sensorised finger is to move the sensorised fingertip along the object surface and to press and then release the object; these motor acts elicit from the tactile sensor signals that can be related to selected features of the object surface (such as roughness, repetitive patterns, edges, corners and holes) and material (such as hardness and thermal properties).

Joint-position and torque signals are necessary for servoing the dc motors; however, they also provide the equivalent of proprioceptive information (i.e. the knowledge of the spatial position of the finger). Associated with simple tactile feedback ensuring that the fingertip is actually touching the object, the recording of successive joint positions allows for the reconstruction of the 3-D shape of the explored object.

A method has been devised for achieving the compliant type of control necessary for tactile exploration, that is for following object surface with the sensorised fingertip while exerting a pressure on it[10]. This method requires the measurement of the normal direction at the point of contact between finger and object, as detected by the tactile sensor. The exploratory strategy implies a motion step along a direction in the plane tangential to the contact point, while the fingertip exerts a predetermined force against the object along the common normal direction. Since the intensity of the contact force and the length of each motor step should be small, accuracy of finger control is particularly important.

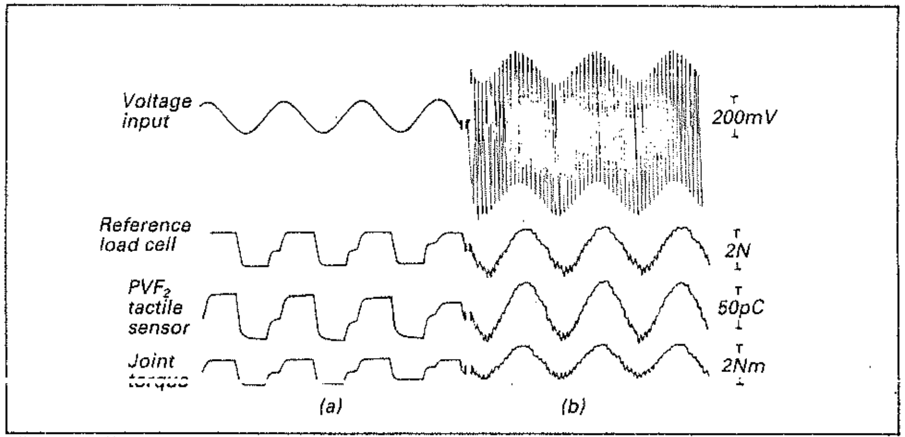


Fig. 4 Effect of the superimposition of high-frequency oscillation at the dc motor driver ('dither'): (a) without dither and (b) with dither. The commanded voltage waveform is shown, along with the actual force waveform, the output of a dermal PVF_2 tactile sensor and the measured joint torque

High friction is the principal drawback of the solution based on cable and sheaths, its advantages being simplicity and, above all, easier and fast control owing to the independence of joint motions.

An attempt has been made to reduce the effects of friction with two artifices: the first is to include those effects into the servo loop by monitoring cable tensions at the outlet of each conduit. The second artifice is to superimpose a high-frequency modulation to the actual voltage waveform commanding each dc motor (a method known in control theory as the 'dither' method).

An example of the efficiency of this control method is given in Fig. 4, where the actual force waveform detected by the fingertip tactile sensor when pressing a reference load cell is shown (a) without and (b) with the superimposition of a higher amplitude, 10Hz dither signal. Furthermore, it was assessed that the minimum force the fingertip could exert when a 0.5Hz sinusoidal torque trajectory was commanded decreased from about 0.6N without dither to about 0.1N with the dither signal.

The skin-like tactile sensor

Human fingertip skin has remarkably complex sensing capabilities, the origin of which has not been fully understood yet[11]. The imitation of those capabilities is the final goal of research in the field of tactile sensors.

In this context the concept of a multilayered tactile sensor has been developed, based on PVF_2 technology[7] and able to provide multiple sensorial information on the physical interaction of the fingertip and the object. The curved sensor mounted on the cylindrical phalanx of the finger comprises a deep ('dermal') sensing layer analogous to that already described for the sensorised platform (but including, in the present configuration, only 35 sensing sites), an intermediate rubber layer to provide compliance to the sensor and protection to the dermal sensor, and a

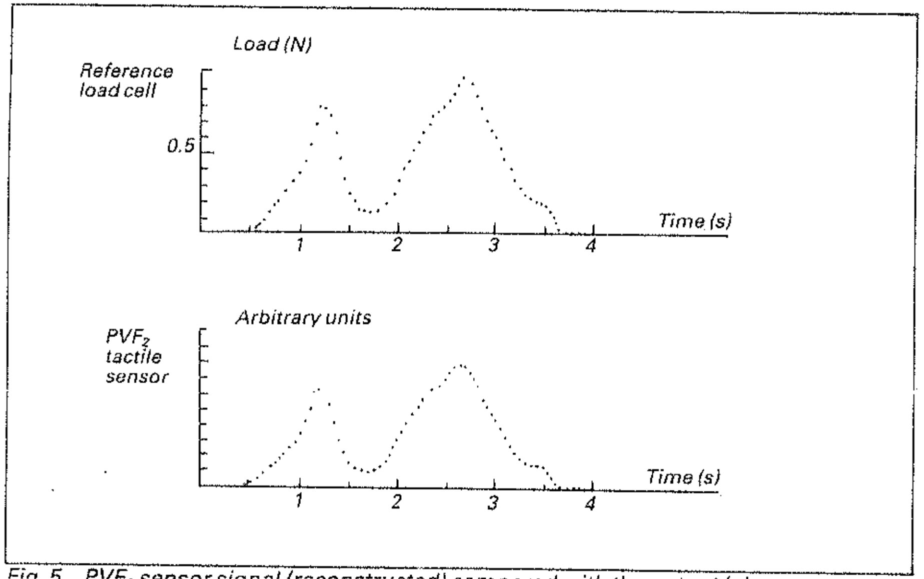


Fig. 5 PVF$_2$ sensor signal (reconstructed) compared with the output (also reconstructed) of a reference load cell

superficial ('epidermal') layer with seven sensing sites concentrated over a small area, that forms a sort of tactile 'fovea'.

The combination of signals detected by each sensing layer allows for the measurement of a number of parameters, such as space and time distribution of contact forces, surface roughness, material hardness and thermal properties.

PVF$_2$ sensors possess very large bandwidth, as demonstrated by the comparison of the signal detected by a PVF$_2$ dermal sensor (connected to a charge amplifier) and those simultaneously measured by the tendon tension strain gauge and by a reference load cell, shown in Fig. 4.

When the tactile sensor is connected, through miniature coaxial cables, to the already described second type of interface device, the tactile matrix can be scanned and the signal in each sensing site reconstructed. In Fig. 5 the 8-bit digitised and reconstructed signal measured by a PVF$_2$ dermal sensor is compared to the actual force exerted on it, as detected by a reference piezoelectric load cell. While the PVF$_2$ signal maintains good fidelity, multiplexing and subsequent processing reduce bandwidth to about 50Hz.

Concluding remarks

A comprehensive approach to the study of tactile sensitivity in advanced robotics has been proposed. It has been pointed out that the human tactile system should be considered as an ideal model to study and possibly to imitate. This assumption involves the opportunity to design the 'hardware' components of an artificial tactile system with reference to their biological analogue. However, the control modalities adopted by the central nervous system are also an attractive and useful model to imitate.

The high-level, goal-directed strategies for tactile perception (and their integration with other sensory inputs) are an intriguing field of investigation for artificial intelligence. However, their comprehension may depend on the ability to model and reproduce in automata the low-level sensory-motor control schemes that form the bases of tactile primitives in humans.

Possible implementations of devices and low-level control methods designed for artificial tactile sensing systems have been illustrated. It has also be shown that the proposed elemental scenario can represent, with some further development and improvement, an adequate test-bed for the study of the elemental exploratory acts necessary for tactile feature extraction and pattern recognition.

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