TENDON ACTUATED EXPLORATORY FINGER WITH POLYMERIC, SKIN-LIKE TACTILE SENSOR

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ABSTRACT

To investigate basic issues related to tactile sensing for robots, a sensorized scenario has been devised which comprises a multisensor static platform and a tendon actuated, 4 degree-of-freedom exploratory finger. Multiple sensory information is fed to the finger control unit: most significant is that obtained through a composite, skin-like tactile sensor, developed in our laboratory and based on the technology of ferroelectric polymers.
In this paper we discuss the design and describe some components of our sensorized scenario. The main features of the articulated exploratory finger are presented and a hybrid type of control, purposely devised for object exploration with tactile feedback, is outlined. Emphasis is also given to the discussion of design criteria for skin-like tactile sensors and to the description of the fingertip multifunctional ferroelectric polymer tactile sensor. Finally, some preliminary experimental results are presented.

1. INTRODUCTION

The usefulness of the sense of touch for advanced, adaptive robots has been increasingly recognized as the practical difficulties to obtain the desired detailed information on environmental conditions through machine vision alone have become evident.

However, while basic research on vision has been favoured by its moderately active nature, by the substantial limitation of the required mechanical hardware and also by the availability of extensive neurophysiological, psyco- physical and anatomical studies, so far research on tactile sensing has been hampered by problems and limitations in all the aforementioned fields. Touch, in fact, is inherently active and requires sophisticated mechanical and electronic hardware, as well as complex sensory-motor control strategies. Moreover, the sense of touch in humans and animals has not been investigated yet with emphasis comparable to vision: for instance, the role of the numerous receptors of fingertip human skin and their mechanoelectric and thermoelectric transducing mechanisms are not yet fully understood. Accordingly, there are not many physiological models to imitate for touch sensing in advanced robotics. Nevertheless, the simple observation of the way in which the sense of touch is exploited by humans to obtain information on the outer world allows to identify the constitutive elements of tactile sensing. In principle, the functions of such elements, the skin, the hand and the central nervous system, should be reproduced in a robot by artificial counterparts: a tactile sensor, an end effector and a controller, respectively.

Based on these considerations we have addressed in our laboratory some basic issues related to the problem of tactile sensing for robots. In this context, we have invested considerable efforts in the development of some hardware tools (both electronic and mechanical) whose availability seems to be preliminar, or at least needs to be pursued in parallel, to further research in the field of "machine touch".
As a first step, we designed a tactile sensor with the aim of fully exploiting the wide range of sensing opportunities offered by sensor-object physical interaction, a distinctive feature of touch compared to vision. Then we designed a single, multi-degree-of-freedom, tendon actuated artificial finger to support the tactile sensor and to perform object exploration. Finally, we have devised a scenario wich integrates a sensing platform, the object(s) to be recognized and the sensorized exploratory finger.

2. SOME GENERAL CRITERIA FOR THE DESIGN OF SKIN-LIKE TACTILE SENSORS.

The present state of the art of tactile sensor technology cannot be considered any longer "primitive", as it was just a few years ago (1). In the recent past several new entries, both from research laboratories and from industrial companies, have increased the average performance of robotic tactile sensors. Presently, at least three models of tactile sensors, each based on a different transducing principle, are commercially available (2).

All the proposed transducers are designed to measure only contact forces and some possess attractive features in terms of force sensitivity and spatial resolution. However, simple contact forces, although extremely important, are only a part of the rich information that can be collected during sensor-object interaction.

In the attemp of following a more comprehensive approach, we have identified the sensing capabilities of the human skin as a model to imitate and have designed a tactile sensor with the specific aim of reproducing such capabilities.

Basically, a skin-like tactile sensor should be installed on a dexterous end effector controlled with a suitable exploratory strategy, and should be able to assess relevant physical properties of the touched object. Alone, or associated with visual and other sensory information, tactile data could be used to recognize an object in a data base of models. As a subsystem of tactile data, sensor-object contact forces are essential to control finger motion during exploration.

In this context, a correct design of an evoluted tactile sensor requires the preliminary definition of a sequence of exploratory actions. The purpose of our sensorized scenario is to facilitate the analysis of tactile exploration by decomposing it in a succession of elementary acts, each easier to study and to reproduce.

In our simplified scenario, and also in most practical cases, a single articulated finger is used to explore objects having dimensions relatively large compared to the sensorized fingertip. A possible sequence of exploratory actions is the following:

1. the position and the shape of the object is approximately defined, usually by means of noncontact (e.g. visual and proximity) or contact (e.g. sensorized platforms) detection techniques. In some particular case these techniques can already provide a full description of an object, but, in general, this procedure is expected to involve long and complex calculations. We intend to verify the possibility to reduce significantly such complexity by complementing proximity and simple contact information with a larger set of data provided by touch;
2. the sensorized fingertip approaches the object and warns against possible dangers. For example, a useful information (obtainable through non contact detection of radiant heat) is relative to dangerous object temperature;
3. the finger softly touches the object. The first information that can be extracted during this step is also aimed to assess dangerous situations, such as local object sharpness;
4. the sensorized fingertip is moved along the object surface. The contact force between the tactile sensor and the object is monitored, along with the spatial position of the contact point, and used as a feedback by the finger control unit. Object shape reconstruction is facilitated by proper choice of the geometrical features of the sensorized fingertip. Reconstruction accuracy is increased by using high spatial resolution tactile sensors;
5. a convenient surface of the object (usually a flat one) is selected and some material properties are further investigated. The first question to be answered can be relative to the thermal properties of the object material: for instance, does the object feel "warm" or "cold"?
6. the cognitive process continues with the investigation of the elastic properties of the object material: is the object "hard" or "soft"?
7. object surface conditions are finally investigated by active exploration. The sensor is moved gently along selected surfaces in order to assess local smoothness or roughness and to detect specific repeated patterns (e.g. threads).

In our present scenario, sketched in Fig. 1, we have deliberately considered only the perceptive steps which precede object grasping: it is intended that collected data would be useful to decide the most appropriate grasping strategy.

In a future, more complex (and realistic) scenario, a multi fingered, tendon actuated, sensorized hand will actually grasp the object and manipulate it. Manipulation is also a powerful cognitive process. Thus, fingertip tactile sensors and proprioceptive (tendon force, joint position) sensors will be used for obtaining further information on object features (for instance thickness and weight), as well as for hand control: for instance an evoluted tactile sensor should detect possible object slippage during manipulation.

The tactile sensor that we have designed is able to contribute (obviously with various degrees of accuracy and reliability) to all the exploratory actions we have described (and underlined for clearness). The basic concepts which justify our design choices are the following:

a) a tactile sensor should provide multiple sensory information, just like the human skin;
b) a tactile sensor should be flexible and conformable to curved fingertip surfaces;
c) being tactile exploration essentially active, sensor dynamic response is crucial.

3. CONSTRUCTION OF A POLYMER TACTILE SENSOR.

To achieve the aforementioned goals, we have developed a family of tactile sensors which progressively approximate the final objective (3), and are based on the same transducing material, i.e. the ferroelectric polymer polyvinylidene fluoride (PVF2). The present design of our PVF2 tactile sensor, shown in Fig. 2, is a slight evolution of the composite, laminated structure described in (4) and extensively tested during preliminary bench experiments. As for the human skin, which comprises several different sensing receptors located inside a mechanically deformable medium, the structure of our tactile sensor includes different sensing and elastic elements, each possessing a specific function. As for the human skin, that behaves functionally like a piezo- and pyroelectric transducer and, accordingly, is essentially sensitive to pressure and temperature variations, our skin-like sensors are piezo- and pyroelectric. Moreover, different sensing elements are purposely designed and appropriately arranged so as to obtain data which complement each other and help solving possible ambiguities.

Basically, our skin-like tactile transducer comprises a deep sensing layer ("dermal" sensor), a relatively thick, intermediate compliant layer and a superficial thin sensing layer ("epidermal" sensor).

The dermal sensor can have sufficiently high spatial resolution (4) and its fabrication technique (that is based on bonding a flexible PVF2 film on a pattern of electrode sites) allows substantial design freedom in terms of sensor shape, dimensions and distribution. The dermal sensor is rigidly supported: thus the PVF2 sensing elements work primarily in thickness mode (i.e. the electric charge generated across the electrodes is essentially related to normal force acting on the sensing site). For the same reason, sensor crosstalk is very small (usually less than 5%), even if sensitivity remains relatively high (detectable force smaller than .05N).

The intermediate rubber layer gives compliance to the transducer and shields the dermal sensor from possible, sudden temperature variations which may occur at the transducer surface and to which ferroelectric polymer sensors, being also pyroelectric, are particularly sensitive. Besides its mechanical role, the intermediate layer might have also sensing functions (4).

The epidermal sensor has low spatial resolution, but very high sensitivity to mechanical stress and temperature variation. As this thin sensor layer is supported by a compliant medium, it is highly deformable. The mechanoelectric transducing mechanisms of this sensor, which are regulated by at least three piezoelectric constants (d31, d32 and d33), are difficult to describe accurately. In general, however, the epidermal sensor operates primarily in membrane mode.

The distal phalanx of our present artificial finger is a perspex hollow cylinder, 28 mm diameter and 40 mm lenght. As shown schematically in Fig. 2, 35 cylindrical rods, 3 mm diameter, are inserted radially through the fingertip wall and define a pattern of 7x5 electrodes on half the outer cylindrical surface. Miniature coaxial cables pass through the hollow phalanx and are individually soldered to each electrode. A 110 micron thick PVF2 film is bonded to the curved fingertip surface and a common electrode established by grounding the outer metallization of the film.

The intermediate, nitril rubber layer is 0.42 mm thick, a value that is a good compromise between the needs for reasonable dermal sensor sensitivity and reduced cross talk.

The superficial sensor has a bilaminate structure, obtained by bonding together two 25 micron thin, selectively metallized and poled PVF2 films. In the present configuration the epidermal sensor has 5 circular sensing sites, located in correspondence with the central area of the dermal sensor array.

A thin layer of conductive paint is deposited on the inner side of the epidermal sensor. When connected to a power supply and resistively heated, this layer forms the basis for the measurement of material thermal properties. In fact, the heat flow variation through the epidermal sensing layer which occurs when the fingertip touches an object is detected and can be related to the thermal diffusivity of the object material.

The output of each sensing element (dermal and epidermal) is sent to an interface unit which comprises analog multiplexing, charge amplifying and A/D conversion circuitry.

From a functional point of view, the epidermal sensor, being directly exposed to the outer world, is very fast and sensitive in detecting small environmental variations. However, its location and its geometrical extension (deliberately limited to a small area of the fingertip) reduce its overall measurement accuracy. Referring to the exploration sequence previously described, the epidermal sensor is expected to provide information on object surface temperature (by detecting radiant heat), contact, sharpness, thermal properties, surface smoothness and slippage.

The signals provided by the dermal sensor, even if smaller, are more easily and quantitatively related to contact force variations than those detected by the epidermal sensor. Thus, this sensor is a sort of "check-point" for the signals detected by the epidermal sensor. Referring again to our sequence of exploratory actions, the dermal sensor essentially measures contact forces with high spatial resolution. Its signals, combined to those from the epidermal sensor, help discriminating ambiguous situations determined by simultaneous mechanical and thermal variations and provide a measurement of material elastic properties.

4. THE TENDON ACTUATED EXPLORATORY FINGER

The second essential hardware component for tactile sensing is an end effector which carries the sensor and brings it in contact with the object to be explored (and grasped). For some limited task a sensorized jaw may be of use. In general, however, an end effector with higher degree of dexterity is necessary for true tactile exploration.

There is a growing research interest on the development of multifingered artificial hands for robots (5). The primary goal is to obtain a better gripper for versatile, secure and adaptive grasp: the intended field of application is the manipulation of industrial components in assembly tasks.

The human hand, an excellent model for robotic end effectors, has the double role of a dexterous prehensile organ and of an efficient sensing device. In our approach, based also on previous work from Hillis (6) and Bajcsy (7), we have clearly privileged the study of the sensorial functions of the hand: actually, we have deliberately neglected, at least in this early research stage, any prehensile function of the device by designing a single articulated finger.

Our basic idea is to analyse in depth the problems related to object tactile exploration, in order to gain the necessary experience for the design and control of a possible future multifingered, sensorized artificial hand.

As for our tactile sensor, we have elected to follow an anthropomorphic approach in the design of the articulated finger: in fact the finger, schematically illustrated in Fig. 1, has 4 degrees of freedom and its joints are actuated by tendons routed through flexible and incompressible sheaths.

Cables and sheats have been preferred to other solutions as actuating means for their simplicity and for the advantages they offer in terms of easy and fast control, owing to the independence of joint motions.

A serious drawback of our solution is high friction. We have reduced its influence on finger control accuracy by monitoring cable tension at the outlets from the conduits with strain gauge devices and including friction effects into the servo loop.

Each joint is actuated via two pretensioned tendons, both driven by a single DC servomotor. Position and velocity are monitored by incremental optical encoders placed on the drive motors.

Finger links dimensions have been optimized by minimizing the condition numbers in the finger workspace. The finger is also expected to be linked to a manipulator wrist to enhance its explorative capabilities.

The control architecture of the finger is outlined in Fig. 1 and shown in more detail in Fig. 3.

As our final task is object exploration, the finger must be position/force controlled. The proposed hybrid control has been designed to provide compliance to the finger, i.e. to keep the sensor pressed on the object with a proper, predetermined contact force. Moreover, while the motion of approach of the finger to the object can be controlled with some of the already described hybrid techniques (8), object exploration cannot rely, by definition, on the "a priori" knowledge of a trajectory. In our control structure, the information provided by the tactile sensor (in particular the location of the contact point on the fingertip surface and the normal and tangential directions, derived from the simple cylindrical geometry of the fingertip sensor) is actively used to generate motor acts.

The overall control structure has been simulated, in a slightly simplified form, with satisfactory results.

An analogic sub-system, which controls joint torques as requested by the devised control architecture, has been actually built and preliminarily tested to evaluate finger and tactile sensor performance.

5. THE SENSORIZED SCENARIO

The skin-like tactile sensor and the supporting, articulated exploratory finger are designed to operate in a scenario that also includes a sensorized static platform.

Basically, the platform has the same structure as the dermal sensor of our laminated tactile transducer. Based on the dimensions of the objects that we plan to recognize, we have designed and fabricated a platform that comprises a matrix of 16x16 circular sensing sites, 6 mm diameter and 8 mm spaced. The sensor is a 110 micron thick PVF2 film. However, overall dimensions and sensor number and disposition are largely free.

The role of the platform in the scenario is twofold and is related to the transducing capabilities of the ferroelectric film, that is sensitive to both mechanical and thermal stimula. In the first part of the exploratory sequence the platform can be used as a pseudo visual, low resolution device by exploiting its pyroelectric sensitivity (9). If the platform (and the object on it) is illuminated by a pulsed, luminous radiating source, a signal is generated in the sensors that are shielded by the object. From these signals it is possible to reconstruct the projection of the object on the plane of the platform and to calculate approximately its position. This information can be used to guide the finger in the first part of its path towards the object.

During actual exploration, the finger presses the object resting on the platform with a contact force that is transmitted to the same platform. Therefore, it is possible to detect reaction forces from the platform: if the platform is assimilated to a degenerated, flat finger, it is possible to find analogies with a situation closer to practice, i.e. a two fingers grasp.

In particular, the sensorized platform provides additional data to identify the object: for instance information on some features, such as cavities, of the hidden side of the object.

6. EXPERIMENTAL

As already pointed out, accurate control of finger joints torque is particularly important to obtain satisfactory performance during object exploration, since it allows the fingertip to press against the explored surface with a predetermined, usually constant, force. The possibility to control the intensity of the local contact forces is an important option to optimize the efficiency of tactile feature extraction and forms the basis for compliant object manipulation.

It is interesting to test the performance of the proposed analogic torque servo system under dynamic conditions and to check the efficiency of the fingertip tactile sensor in the same experimental situation.

In a preliminary experiment, the spherical probe (R=3mm) of a piezoelectric, calibrated load cell was used as the test object, against which the sensorized fingertip, under the control of the torque servo subsystem, was pressed. During the experiment, all the finger joints were locked, except the one actually controlled.

The ability of the analogic servo subsystem to impart the desired torque to a joint and to control it was evaluated by imposing a variable voltage input to the servo. Input voltage waveform, actual joint torque (measured by strain gauge devices), dermal and epidermal sensor signals and load cell output were simultaneously monitored in the two significative situations of commanded sinusoidal and step torque trajectories. Experimental results, reported in Fig. 4, prove the satisfactory response of the torque servo system and confirm the good performance of PVF2 tactile sensors.

7. CONCLUSIONS

Progresses in the field of tactile sensing for robots will require substantial contributions from different areas of science and technology. However fashinating the proposed uses of touch may be, they would remain little more than speculations without prior development of complex hardware tools, such as tactile sensors and dexterous end effectors.

In this paper we have attempted to organize the different constitutive elements of tactile sensing (with emphasis on the hardware components) in a simplified, structured scenario.

One of our expected goals was to derive from the analysis of tactile cognitive actions within the scenario a feedback for more effective design of advanced tactile sensors and end effectors, here considered as fully integral and active parts of the system.

Obviously, further efforts are needed to prove the usefulness of our approach. Towards this aim, work is in progress to complete the elements of the scenario and integrate them in a computerized system.

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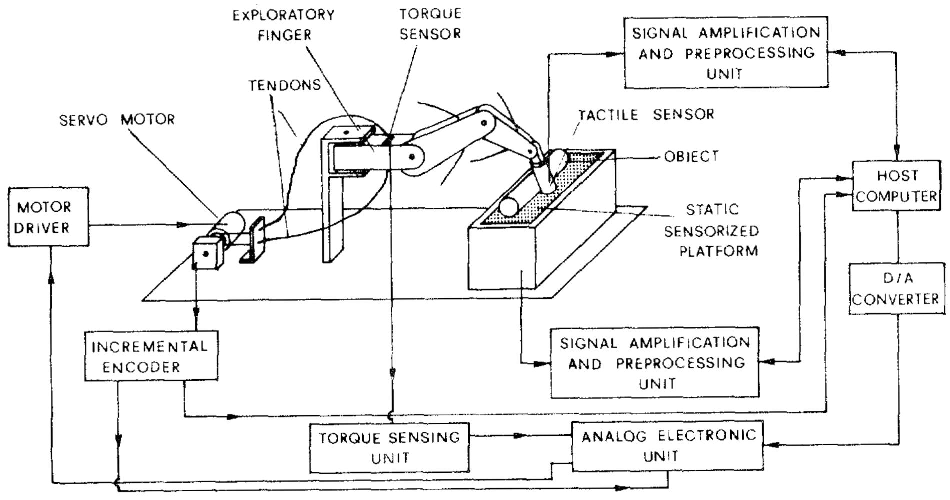

Fig. 1 - The tactile exploratory system and its main control features.

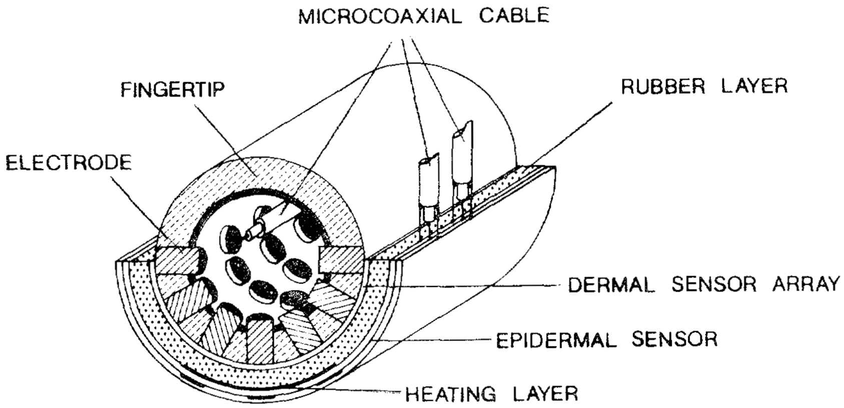

Fig. 2 - The composite fingertip tactile sensor.

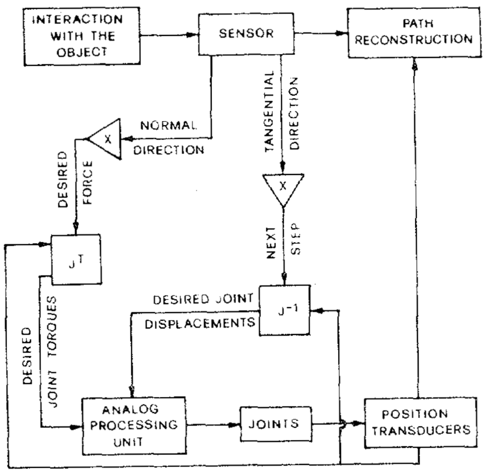

Fig.3 - Block diagram of the proposed hybrid control.

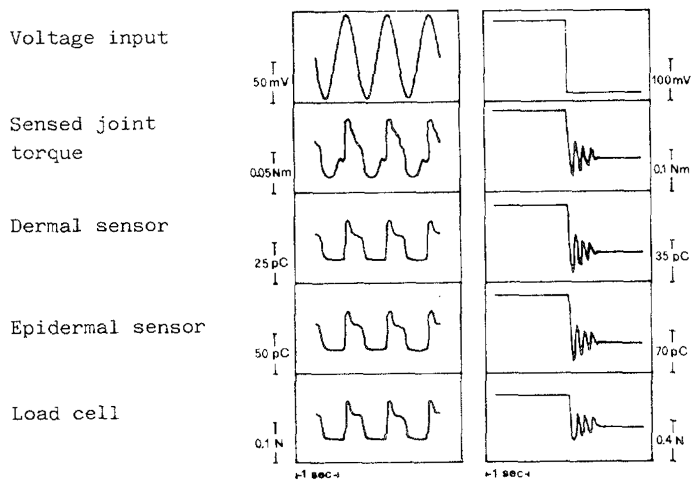

Fig. 4 - Finger response to commanded sinusoidal (left) and step (right) torque trajectories.