ROBOT TACTILE PERCEPTION

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Abstract

In this paper we discuss some fundamental issues related to the development of an artificial tactile sensing system intended for investigating robotic active touch. The analysis of some psychological and psychophysical aspects of human tactile perception, and a system design approach aimed at effectively integrating the motor and sensory functions of the robot system, suggested to conceptually organize tactile exploratory tasks into a hierarchical structure of sensory-motor acts. Our approach is to decompose complex tactile operations into elementary sensory-motor acts, that we call "TACTILE SUBROUTINES", each aimed at the extraction of a specific feature from the explored object. This approach simplifies robot control and allows a modular implementation of the system architecture: each function can be developed independently and new capabilities can easily be added to the system. All tactile exploratory procedures are selected and coordinated by a high-level controller, which also operates the integration of tactile data coming from sensors and from lower levels of the hierarchy.

Some experimental results will be presented demonstrating the feasibility and usefulness of tactile sensing in exploratory operations. A recently developed sensor will be briefly presented, which exploits force/torque information measured directly at the tip of the robot end-effector. This sensor is able to detect, besides the position of the contact point, the normal and tangential components of the contact force. Methods for characterizing the surface of manipulated objects, according to their hardness, texture and friction properties will also be discussed.

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1. Introduction

Tactile perception is a fundamental capability for a robot that has to execute manipulative and explorative tasks. The interactive behavior of touch allows humans to extract several features from the external world, that cannot be detected by vision or other senses. Examples of such features are: hardness, elasticity, roughness, texture, temperature, thermal conductivity and local geometrical characteristics, such as holes, edges, cavities, sharp regions, etc.

It is important to point out that extracting such features from an object is not a capability of a specific sensor, but it is rather a capability of the whole system. Performing explorative tasks involves the execution of sensory-motor procedures, in which tactile information is used to sense and drive the movements of the fingers. Touch is intrinsically active and involves dynamic sensing, where movements are utilized for augmenting and driving sensory information. The coordination of sensory activity and motor activity is not just a summation of capabilities, but it considerably improves robot performance, by increasing the perceptual skill of the system and extending the set of characteristics that can be extracted from the external world.

In passive perception (mostly followed in vision), sensors and actuators are physically separated: sensors are fixed devices which statically observe the world and send information to a central controller at a very low sampling rate; once sensory data are analyzed, a motor action for the manipulator is planned. In this approach, data processing and motion planning are two distinct processes, which do not overlap in time. Motion planning is based on sensory information, but once the trajectory of the arm has been calculated it cannot be changed.

In active perception, especially in tactile perception, sensing and control are tied together. Sensors are often mounted on actuators and are used by the system to probe the environment and precisely control the movements. Trajectories are computed in real time using sensor-based control techniques.

Assigning perceptual capabilities to exploratory acts rather than to static sensors is a novel concept in robotics, that has not received much attention among scientists so far, unless at the level of speculation. Recently, however, this issue has been considered more seriously, and some implementation has been attempted [1][2][3].

Our goal is to build an autonomous tactile robot system capable to perform active exploration and fine manipulation of real objects, for their recognition.

Based on the analysis of some aspects of human tactile perception, our approach is to decompose complex tactile exploratory procedures into a sequence of elementary sensory-motor acts, that we call "TACTILE SUBROUTINES", each aimed at the extraction of a specific object feature [4].

In humans, it is possible to identify a number of typical tactile procedures that are performed with the fingers every time we want to detect some particular feature from an object. For example, if we are interested to know the hardness of a material, we repeatedly press our fingertip against the object surface, paying attention to the force we exert and to the object deformation. If we are interested in object texture, we gently slide the fingertip along the object surface and we pay attention to the tactile sensation coming from our epidermal sensors. As another example, if we want to reconstruct the shape of an object, we follow the object contour, keeping in mind the trajectories of the contact points achieved by the fingertip.

In this context, we define a "TACTILE SUBROUTINE" as a motor action executed on a sensor, guided by the tactile information coming from the sensor itself, according to a control strategy which depends on the sensor and on the feature that has to be extracted.

This approach considerably simplifies robot control and allows a modular implementation of the system architecture: we can develop one tactile subroutine at a time and freeze it in the system as "innate behavior". To add capabilities to the robot we simply insert new subroutines in the system. All tactile subroutines are selected and coordinated by a high-level controller, which also operates data integration and directs the global exploratory strategy.

2. System description

The tactile system we developed for investigating tactile perception consists of the following components:

- a PUMA 560 robot arm, controlled by its dedicated microprocessor (UNIMATE) and programmed in VAL II;
- a miniaturized force/torque (F/T) fingertip sensor, working as a sensitive probe for tactile exploratory tasks;
- a piezoelectric polymer (PVF2) sensor, implementing a sort of artificial finger nail, intended to rub rough surfaces for texture detection.

Other components of the system are two PC's, utilized for sensor preprocessing, and a DEC micro VAX II, used as a system supervisor for tactile data integration and high level control.

The complete architecture of the system is depicted in Figure 1. The fingertip F/T sensor is mounted on the PUMA wrist and the nail-sensor is attached to the fingertip. Each sensor is connected to a PC. PC1 is intended to process the information coming from the F/T sensor and to control the execution of tactile exploratory procedures; PC2 is dedicated to the nail sensor and works as a slave in the communication with PC1. It continuously read the signal produced by the nail during the sliding movements and computes a number of parameters useful to characterize roughness. The two PC's communicate via serial line. PC1 is also connected to the PUMA processor through a 16 bit input/output parallel port for managing sensor-based movements.

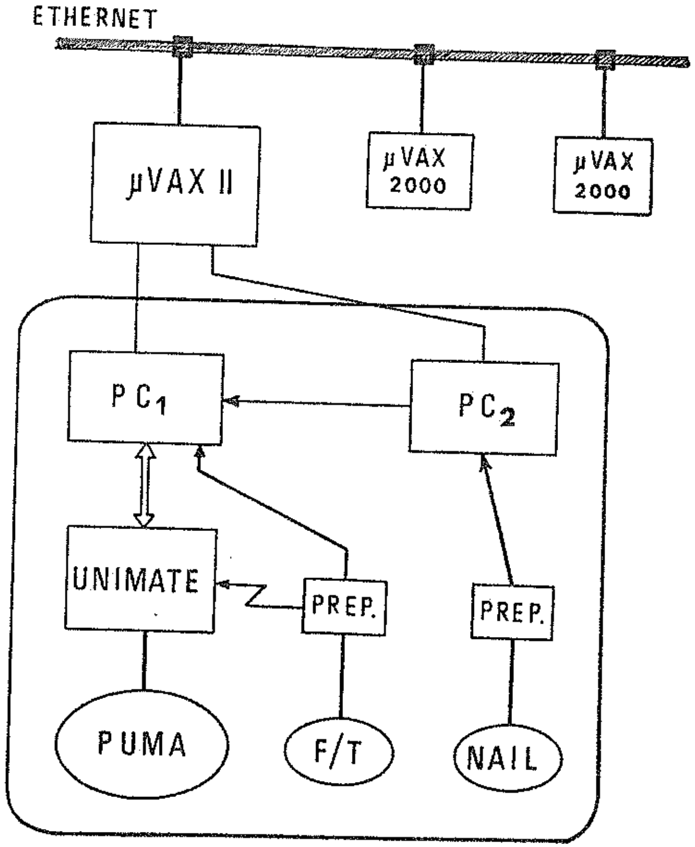

Fig 1. The system architecture.

An additional parallel interconnection exists between fingertip sensor and PUMA processor, which implements a sort of reflex pulse for stopping the PUMA in case of dangerous situations (overloads on the sensors) that could damage the system.

2.1 The F/T sensor

This sensor has been designed to be easily incorporated as a sensitive fingertip in an articulated robot hand, but in the system presented in this paper it is used as a tactile probe for exploratory tasks and it is mounted on a single rigid "finger". This finger is connected to the PUMA wrist through a compliant adaptor: in fact, a certain amount of flexibility is mandatory for controlling interaction forces between robot and environment. A schematic description of the sensor is shown in Figure 2.

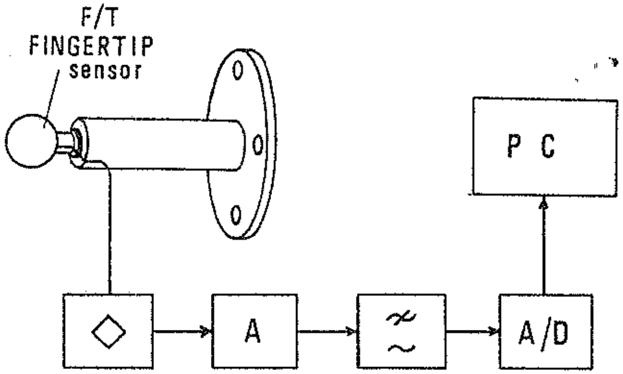

Fig. 2. The fingertip force/torque sensor with its conditioning units.

The device has the purpose of measuring the three orthogonal components of the resultant force and the three orthogonal components of the resultant torque applied to its mechanical structure. The measurement principle is the mechano-electric transduction of the elastic strain of a monolithic cylinder beam to which the load is applied. The transduction is carried out by 6 strain-gages only.

The top of the cylindrical structure is threaded so that different types of fingertips can easily be adapted to the sensor. When an external force is exerted on the fingertip, the mechanical structure of the sensor deflects, causing the strain-gage response.

The electric resistance variation of each strain gage, due to the strains imposed to the cylinder by the load, is separately measured. This information can be processed in the form of six orthogonal components of the applied force/moment by solving the set of linear equations which model the elastic compliance of the structure; the equations can be obtained by using beam theory or by calibrating the cell experimentally. Conventional algorithms for linear system solution, e.g. Gaussian elimination, are adequate for this purpose. However, the peculiar arrangement of the strain gages on the cylindrical surface of the sensor allows a more time-efficient algorithm, almost decoupling the cell readings [5].

The small size of the sensor, the low cost, along with its simple structure, make it attracting for being integrated in the mechanical structure of robot hands or robot end-effectors for fine manipulation.

Some performance figures experimentally obtained from a prototype sensor, using a non-engineered technology, are listed in table 1.

Table 1

Active cell size:	10 x 10 x 16 mm^3
Force range:	0.1 to 30 N
Torque range:	0.1 to 30 Ncm
Crosstalk (max):	4% FSO
Precision (repeat.):	2% FSO

The thickness of the cylindrical beam is a free parameter which determines the loading range of the sensor. Temperature variations can be compensated by using an extra strain-gage, bonded to the stiff base of the sensor structure.

Resistance variation of each strain-gage is measured by an individual Wheatstone bridge (module ◊ in Fig. 2); the 6 output signals are then amplified (A), filtered out by a low pass filter (~), multiplexed and finally converted into digital form (A/D). The F/T sensor is connected to a PC through a Data Acquisition Card, which performs multiplexer addressing and analog to digital conversion.

2.2 The PVF2 sensor

A piezoelectric sensor, made by PVF2 polymer, is utilized as a dynamic sensor for implementing a sort of artificial fingertip nail, intended to rub rough surfaces for texture detection [2]. The nail structure consists of a properly shaped plastic sheet, adapted to the upper surface of the fingertip, from which it protrudes for about 5 mm (Figure 3).

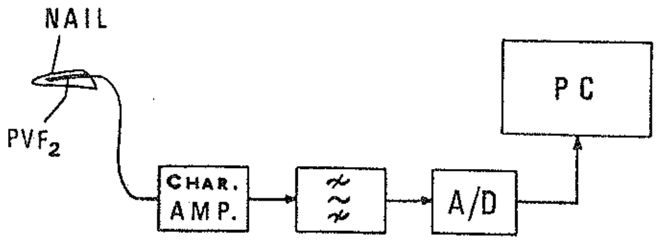

Fig. 3. The PVF2 nail sensor with its conditioning units.

This arrangement allows to add compliance to the sensor and to increase sensor sensitivity to mechanical vibrations. The PVF2 film (25 micron thick), used in a bilaminate configuration, is located between nail and fingertip, bonded to the inner side of the nail.

When the nail is slid along a rough surface, the nail structure vibrates, producing strain in the PVF2 sensor, which generates an amount of charge proportional to the strain. This charge is amplified by a charge amplifier and the output voltage signal is digitized by an A/D converter and processed by another PC.

The upper frequency limit of the digitized signal, established by the sampling rate of the system, is almost 5 KHz, and it proved to be sufficient for all practical surface explorations.

As for all piezoelectric sensors, the lower frequency limit of the nail signal is not zero, but a few hundreds mHz. This is due to the finite time constant of the piezoelectric sensor, that derives from its finite internal resistance. In this particular case, such intrinsic limitation turns out to be a positive feature of the sensor: in fact, as a consequence of a non-zero lower frequency limit, the nail cannot respond to very slow mechanical deflections. Therefore the high frequency components of the signal due to the roughness of the explored surface are detected, while the low frequency "noise" caused by the variation of the contact force during the sliding movement is filtered out.

An approach involving dynamic tactile sensing for texture detection using a PVF2 sensor has also been reported by Cutkosky [6].

3. Functional architecture

Based on the functions that the robot system is intended to implement, the software architecture has been organized in three control levels, as illustrated in Figure 4.

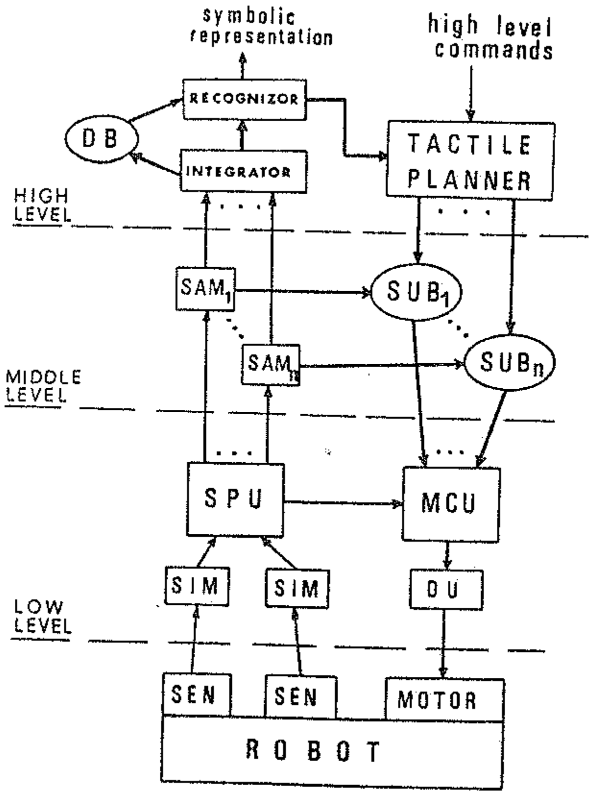

Fig. 4. Hierarchical functional architecture of the system

Level 1

The lowest level of this hierarchy includes all VAL II programming and all assembler routines for sensor acquisition, processor communication and actuator driving. This level is designed to execute simple commands sent by the middle-level controller. Such commands may include position commands in joint space or in cartesian space, or force/torque commands.

The Sensor Interface Module (SIM) realizes the interface between sensor and computer, providing analog to digital conversion and data acquisition. The Sensor Processing Unit (SPU) performs a first stage of processing and provides the Motor Control Unit (MCU) with feedback signals for motor control. According to the middle-level commands and to the feedback signals, the MCU computes the proper output data, which are converted in analog voltages and then sent to the Driver Unit for driving the motors. VAL II programs are included in this module.

Level 2

The middle level is the level in which elementary sensory-motor operations (tactile subroutines) are frozen in separated modules (SUB_i) as behavior of the system. Each subroutine has the role of managing the execution of an exploratory procedure aimed at the extraction of an object feature. The exploratory strategy depends on the feature that has to be extracted and on the sensor used in the exploration.

A dedicated Signal Analyzer Module (SAM), one for each subroutine, performs a compression of sensory data coming from the lower level, by computing some significant and synthetic parameters utilized as feedback signals for the middle-level controller. The same parameters are also combined in a next stage for computing a quantity representative for the feature extracted by the tactile subroutine. All outputs produced at this level are sent to the high level for further processing.

Level 3

The purpose of the high level in this architecture is to plan an exploratory strategy according to the input task and to attempt a recognition or a classification of the objects explored by the robot system. All data and parameters computed by the middle level converge in a module, called Integrator, whose task is to merge all sparse sensory data into few synthetic quantities compatible with the information stored in the Data Base.

The real recognition process is performed by the Recognizor module, which compares the parameters extracted by the Integrator with sample parameters stored in the Data Base. This sample parameters are extracted from a number of sample objects in a previous learning phase, carried out by using the same procedure.

In this way, the system learns how to build its own model of the world, since only internally processed information is utilized to construct and update the Data Base. In this way, systematic errors and imperfect calibration do not affect the system performace significantly, and the recognition process comes out more robust.

The Tactile Planner selects the next tactile subroutine for optimizing the recognition process, according to the input task and to the local features recognized during tactile exploration (given as feedback information in the high-level controller).

4. Experimental results

Three tactile subroutines have been implemented on this system, HARDNESS, TEXTURE and FRICTION, aimed at the extraction of hardness, texture and friction coefficients respectively.

In all experiments the objects were fixed on the table, located in a position known *a priori* by the robot, since no vision system was used to identify absolute positions in the robot workspace. All tactile subroutines were coordinated by PC1.

4.1 Hardness procedure

Starting from an initial configuration, the arm moves slowly toward the object, in order to press the object surface with the sensor tip. When the contact force detected by the F/T sensor exceeds a given threshold, say F1, the PUMA stops its motion and sends the coordinates of its wrist to PC1. After the transmition is completed, the PUMA slowly increases the contact force on the object (as allowed by the compliance of the wrist adaptor) and when the force on the F/T sensor reaches a second threshold F2, the PUMA stops again and sends the new wrist location to PC1.

Based on the information received from the PUMA and on the elastic properties of the compliant wrist adaptor, PC1 determines the position displacement D of the F/T sensor during the pushing procedure and computes the following ratio:

$$H = \frac{F2 - F1}{D}$$

In the case of soft materials, the displacemet D caused by object deformation will be relatively large, while for hard objects D will result much smaller. Thus, the parameter H represents a rough estimate of object hardness.

Figure 5 shows the results obtained by executing the procedure on several sample objects, having the same shape (parallelepipedal), the same thickness (10 mm), and modulus of elasticity comprised between 10^5 and 10^9 Pa.

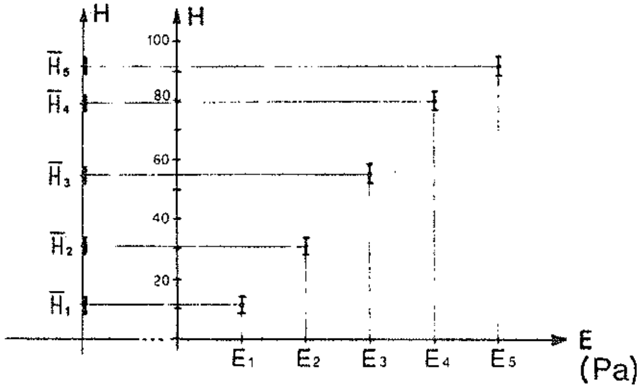

Fig. 5. Statistical evaluation of the H parameter, executing the procedure on five sample objects.

Repeatibility was also tested by running the procedure several times on each object: the standard deviation computed over 20 tests on the same object did not exceed the value of 4% F.S.O.

4.2 Texture procedure

This tactile subroutine was executed by rubbing the PVF2 nail sensor (located at the tip of the F/T sensor) on the object surface with a predetermined force. Since fine texture details are better perceived by exploring planar surfaces, we used flat objects only. Moreover, in order to symplify signal processing and easily describe roughness by few sinthetic parameters, we decided to test the system by using "wrinkly patterns", prepared by disposing in parallel thin wires on a smooth board. We used spacing between wires and diameter of the wires as parameters for characterizing roughness. Wrinkly patterns have also been used by psychologists to test the human tactile system [7][8]; therefore they also represent a good method for comparing the human perceptual system with an artificial one.

The procedure has been caried out by rubbing the nail sensor on the wrinkly patterns along a straight line, for a length of 35 cm, at the speed of 125 mm/s. The force exerted on the surface was set at 3 N and controlled by PC1, while the nail signal was sampled by PC2 at the frequency of 3.2 KHz. The aim of the experiments was to test the ability of the system in discriminating spacing and thickness of the wrinkles.

Signal processing following the exploration of each pattern included a filtering phase, a thresholding phase and an evaluation phase, where two parameters were computed on the signal: the distance d between spikes and the amplitude A of the spikes. In particular, if n is the number of samples acquired between two spikes, v is the velocity of the exploration and f the sampling frequency, spacing is given by: $d = nv/f$.

Results of these experiments are reported in Figure 6: Figure 6a shows the parameter d vs. the real spacing of the wrinkles, while Figure 6b shows the parameter A vs. wrinkle thickness.

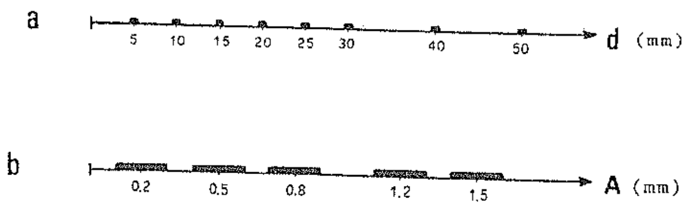

Fig. 6. Statistical evaluation the Texture Procedure.
Fig. 6a: parameter A related to wrinkle amplitude
Fig. 6b: parameter d realted to wrinkle spacing.

The system exhibited a precision of about 0.2 mm in perceiving distancies, but its tactile acuity (i.e. the smallest distance at which the system is able to discriminate two wrinkles as distinct) resulted of 0.5 mm. This greater value can be explained by considering that a spike produced by a wrinkle fades out in about 3-4 ms, depending on the elasticity of the nail, and at the speed of 125 mm/s the nail advances of about 0.5 mm.

The standard deviation calculated for the parameter A was much greater than the standard deviation calculated for d. The main factor affecting the value of A is the mechanical vibration of the robot arm during the exploratory procedure. However, the system was able to discriminate five wrinkles (0.2, 0.5, 0.8, 1.2 and 1.5 mm thick) with an error smaller than 15%, and four wrinkles (0.2, 0.6, 1, 1.5 mm thick) with an error smaller than 2%.

4.3 Friction procedure

This procedure involves automatically testing the friction properties of an object, in order to estimate its static and dynamic friction coefficients. This information is very useful for programming operations like grasping or manipulation of objects, which often rely on the forces the friction is able to withstand; beyond that, it can be used in order to characterize different objects, contributing to their recognition.

The way the friction coefficient is estimated is inspired by the observation of human behavior: we usually proceed by touching the object with a finger, pressing on it moderately and then exerting on the finger a force tending to slide it over the object surface; this force is increased until the fingertip actually slips, after which the operation is over.

To replicate such an operation, an automatic system needs the capability of sensing both the normal and tangential forces exerted at the contact point. This feature, which is not possessed by most conventional tactile sensors, is realized by the so-called Intrinsic Tactile (IT) sensor, as described by Bicchi and Dario [5]. An IT sensor consists basically of a force/torque sensor integrated within the fingertip surface, so that all the components of the force system generated by contact pressures are measured. If the geometrical description of the fingertip surface is known, it is possible to apply simple algorithms (as the original one proposed by Salisbury [9], or a more precise one described in Bicchi [10]) so as to obtain the following information:

a) the location of the contact point on the fingertip surface;
b) the intensity and direction of the contact force, and hence
c) the values of the normal and tangential (friction) components of the contact force.

Using the miniaturized F/T sensor mounted on the Puma arm and a spherical fingertip of radius 10 mm, fixed in turn to the F/T sensor, we performed several experiments aimed at automatically measuring the coefficients of static (μ_s) and dynamic (μ_d) friction of different objects in contact with the fingertip. The fingertip was initially brought to touch the object surface with a normal force of about 0.5 Kg; then the robot arm started to force it to move in the tangential direction, increasing this force linearly with time. The values of normal and tangential components of contact force, detected by the IT sensor during this phase and the following slippage, were stored in a buffer memory. Once arm motion is stopped, data are elaborated and presented in graphic form as shown in fig.7.

The diagram showed in fig.7 refers to an experiment with a rubber object (with relatively high friction), and presents the plot of friction ratio R_f (i.e. the ratio between the tangential and the normal component of contact force) vs. time. Each small square in the plot corresponds to a value of R_f measured at a sampling rate of 10 Hz. In the diagram of fig.7 two parts can be easily recognized: in the first part R_f increases almost linearly, until a maximum is reached, after which the friction ratio drops to a lower value; in the second part R_f is approximately constant. The interpretation of such plots is straightforward: the friction force increases until R_f reaches the static friction limit μ_s, then motion (slip) starts, and, according to the Coulomb model of friction, the friction ratio drops to μ_d.

Due to the fact that accidental perturbations of the mechanical system and of the sensor measurements superimpose random oscillations to the experimental curves, their

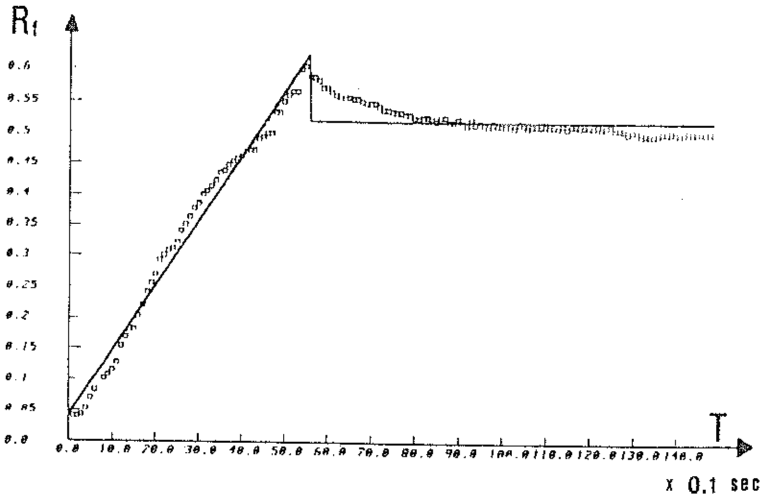

Fig. 7. Friction ratio during a sliding movement

interpretation in terms of quantitative estimates of ms and md is not obvious. Repeated experiments on the same objects resulted in data having a common pattern, but several local discrepancies. An algorithm for interpreting such data that resulted in fairly repeatable estimates is the following: the set of measurements is splitted in two parts corresponding to a tentative slippage instant T_S; the first subset of data is fitted with the best line in least-squares sense, and the second subset is aproximated with a constant value equal to its average value. The sum of the averaged squared errors in each data subset is assumed as a measure of approximation; at varying T_S, the slippage instant is found as the one minimizing the approximation error.

The resulting linear approximation is presented in Fig.7 with a superimposed solid line. The maximum value of friction ratio reached before slippage is assumed as the static friction coefficient; the average value of the following phase is the exstimated dynamic friction coefficient.

Based on the above technique, an automatic sorting of objects, having different friction characteristics, has been attempted. Objects belonging to three classes, with low, intermediate and high friction, were examined in random order by the system and the friction of their surfaces measured with the above described methods. The objects were then recognized as belonging to one out of the three classes: the incidence of errors in these tests was virtually null.

5. Conclusions

A sensorized robot system able to perform specific exploratory procedures (tactile subroutines) on objects in order to extract information useful for their description, has been described.

The approach we have proposed is an attempt of replicating in an artificial system some of the sensory-motor paradigms used by humans in exploratory tasks. Obviously, many simplifications were introduced to reduce the complexity of control and the amount of computation on the sensor signals.

In spite of the limitations of the present work and the rather simple structure of the system, results show the validity of this approach. Studying one finger exploratory strategies based on the decomposition of complex human tactile perceptual activities in a sequence of elementary sensory-motor acts, seems to be promising and to encourage further investigation in the field.

Acknowledgements

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