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Dear Dr Bicchi

re: IFAC Symposium on Robot Control (SYROCO '85), November 1985,
Barcelona, SPAIN

I am pleased to inform you that we have now received the manuscripts for the Proceedings volume of the above and your manuscript is one chosen to appear in that volume.

Copies should be ready for publication in December of this year.

Should you require any further information please do not hesitate to contact me.

Yours sincerely

Maureen G. Morris

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ON THE CONTROL OF A SENSORIZED ARTIFICIAL FINGER FOR TACTILE EXPLORATION OF OBJECTS

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Abstract. This paper deals with a basic problem of machine perception: assuming that an ideal tactile sensing device is available, how an advanced robot could use it effectively to explore and recognize objects?

This issue is addressed by describing first the features of the ideal tactile sensing device. Then a sensor-based control method is proposed, allowing a pluriarticulated manipulator equipped with such an ideal device, to perform the elemental surface-tracking task of object tactile exploration.

Real tactile sensors are not ideal under many respects: the nature and relevance to the control matter of sensor limitations are examined. The proposed method is then modified in order to control a pluriarticulated manipulator provided with a real tactile sensor during exploratory operations.

The main features of both control methods are discussed with reference to the particular case of a 4 degree-of-freedom finger-like manipulator.

Keywords. Compliance; hybrid control; active touch; tactile sensors; tactile exploration; sensor-based control; robot perception.

INTRODUCTION

A vast and persuasive literature documents the moment of tactile information in the enhancement of advanced robots capabilities (Coiffet, 1983) (Harmon, 1982) (Dario, 1985a). Gaining information on the environment surrounding the robot through touch requires an active sensing system comprising a tactile sensing device, a mechanical frame to move and press the sensor against objects during exploration, and a control architecture to manage the whole process (analogies with the human skin, hand and nervous central system are evident). A possible scheme of the organization of such an artificial tactile sensing system is shown in Fig. 1.

We have addressed sequentially the development of each component of a robotic tactile sensing system. A composite ferroelectric polymer (PVF2)-based, skin like tactile sensor has been devised and constructed first (Dario, 1984a). Then a finger-like mechanical device has been developed as a simple exploratory system able to anticipate the features of the dexterous hands of future, sophisticated robots (Dario, 1985b). Some fundamental issues have been considered in the design and realization of this finger, e.g. optimal dimensioning of links and actuation of distal joints by means of remote motors.

The finger, schematically illustrated in Fig. 2, incorporates various information sources: a PVF2-based, curved tactile sensor on the fingertip, and joints position and torques transducers.

The problem of managing those inputs and commanding proper exploratory motions and forces for tactile exploration can be approached in general terms. In this paper we discuss a sensor-based control strategy that has been devised as a solution to this problem.

THE IDEAL TACTILE SENSOR

The most desirable features of a tactile sensing device intended for object exploration can be classified as follows:

a) **Geometrical features.** A tactile sensor is expected to recognize, when touching an object, at least one point belonging to the object surface and the direction normal to that surface in that point (whenever it can be defined).

In order to obtain this information, an ideal sensor should be featured by infinite spatial resolution and double-curved and regular (with no edges) surface. The spherical shape is particularly convenient, as the said normal direction is simply the radius passing through the contact point (the excited sensing site): hence complex calculations can be avoided. Since neither the object nor the sensor are rigid bodies, the contact will not be truly punctual, but rather a small sensing area will be stimulated. Actually compliance is often a desirable characteristic of the fingertips surface, especially when also manipulating tasks are assigned to the robot end effector. In this case, as many (theoretically infinite) sensing sites are located in that area, the notion of "contact point" and "normal direction" should be reconsidered. For the sake of simplicity, however, we assume that a contact point and a normal direction can be identified from the tactile sensory data during sensor-object interaction.

b) Sensing features. In order to control the pressure of the fingertip on the object, the sensor should possess a linear, non hysteretic, response to the exerted pressures.

Besides, friction between fingertip and object should be negligible, to reduce control disturbances and sensor misreadings.

Additional information about the physical characteristics of the object, such as its thermal diffusivity or surface smoothness, can be collected by some skin-like tactile sensors (Dario, 1984b). Despite the potential usefulness of such data for object recognition, sensory features of that type do not concern directly the present control matter.

A CONTROL STRATEGY FOR TACTILE EXPLORATION

Tactile exploration essentially consists in following object surfaces using the information on contact features collected while the exploration proceeds.

By its own nature, tactile data acquisition requires the sensor to be simultaneously moved along and pressed against the explored surface. Hence, such a task calls for a control method of a "compliant" type (Mason, 1982).

However, tactile exploration is quite different from such tasks as inserting a peg into a hole or placing an object on a table, which are often cited as examples of operations requiring "compliance" in control. In fact, if we refer to the organization of the robot environment in terms of a "base" fixed coordinate frame and a task suitable "compliance" frame (Paul, 1981) it is possible to notice significant differences between the two cases.

Operations which are normally considered to need compliant control have, in most cases, a position trajectory assigned in terms of base coordinates; this trajectory may be modified during its execution, if contact forces or tactile stimuli are detected, accordingly with the compliance specifications given in the appropriate frame. On the contrary in the case of tactile exploration the task is completely specified in the compliance reference frame.

Base frame related position trajectories have not to, and cannot, be previously assigned, since the motion of the exploratory device is determined in real time by sensory feedback.

Let us consider for example the sensor depicted in Fig. 3 which, incorporated in a suitable end effector, follows the surface of an unknown object while being pressed against it (actually Fig. 3 refers to a cylindrical real sensor, that will be described later).

In a compliance frame fixed to the fingertip, so that its z-axis passes through the contact point and coincides with the direction normal to the surface, the task will be specified as follows: "move in the direction of the x-axis (or in any direction which lies in the x-y plane) while exerting a proper force along the z-direction". This procedure allows to define a sequence of points belonging to the surface of the object. The knowledge of these points and of the tangential directions in each one of them, allows to reconstruct, by interpolation, a spatial curve lying on the object surface. Finally, under some hypotheses, the shape of the object can be obtained from a number of those curves. Such an exploratory strategy, that is similar to that often observed during blind tactile exploration in humans, has already been proposed by R. Bajcsy (1983); however, control problems were not investigated in their generality there.

Exploring a surface is a surface-driven task: one does not know the way the fingertip will go, but knows that the path followed belongs to the surface of the explored object. Since it needs force to be commanded along certain degrees of freedom and position along the remaining ones, tactile exploration requires a hybrid control (Mason, 1982). However, none of the hybrid control methods proposed so far, among which fundamentals are those described by Raibert and Craig (1981), Salisbury (1980) and Zhang and Paul (1985), are suitable for this task.

In fact, the heart of each one of those methods consists of checking the compatibility between the desired force and position trajectories, given in the fixed coordinate frame, and the compliance specifications, expressed in the compliance frame. In all the different methods this check is done by means of "compliance" or "stiffness" matrices. On the contrary, our tactile exploration strategy provides force and position commands which inherently satisfy (unless sensor imperfections) the physical constraints imposed by the contact.

Since it does not involve either compatibility checks or coordinate transformations (except those between compliance frame and joints space), our hybrid controller is much simpler and faster than the above mentioned methods (which would have been by far too time-consuming to be used in our task). Of course, our non-deterministic way of driving a manipulator cannot be extended to control tasks other than tactile exploration.

Actually, in a more general approach to the problem of object handling by robots, the proposed method should be regarded as a recurring phase in a higher level perceptual strategy managing various manipulative and exploratory tasks. Obviously, hardware and/or software means should be provided to prevent the device from exceeding its structural limits when an unknown, possibly dangerous surface is explored (see Fig. 1).

Exploration with ideal tactile sensors. Let us consider in some detail the control scheme illustrated in Fig. 4, that refers to the case of our articulated exploratory finger.

The fingertip sensing elements are scanned and the corresponding signals processed so as to be interpreted by the control computer as an array, whose elements correspond to the normal pressure detected by each sensing site. The unit vector normal to the object surface in the contact point is expressed in the fingertip frame by means of fixed geometrical relationships between the sensing sites and a coordinate frame fixed with the fingertip.

Exerting a force along a certain direction of this frame requires applying to the manipulator joints a set of torques that can be calculated by applying the Jacobian transpose matrix to a vector of the same direction (Paul, 1981). Hence, if the aforesaid normal unit vector is used, joint torques producing a unit force normal to the object surface can be calculated. If this result is scaled by the error between the actual contact force intensity (as measured by the tactile sensor) and the desired force, a feedback-type control is exerted over the force itself. The torque error signals evaluated in this way are then processed by a suitable "torque control law" algorithm.

As far as the control of exploratory motions in the plane tangent to the contact point is concerned, one vector contained in that plane is chosen (this choice is at disposal of the higher level controller) and expressed in the fingertip reference frame; then it is multiplied by the desired lenght of the exploratory steep. The resulting vector is applied to the Jacobian inverse matrix, thus generating the angular displacements of each joint which originate the desired motion of the fingertip.

The error caused by approximating finite with differential relationship can be obviously limited by reducing the lenght of the motion step, at the expenses of exploration speed. The successive desired fingertip displacements are summed in a register to allow the joints to track the desired position trajectory even if disturbed by the friction between the fingertip and the object. During each computation cycle, this register is updated and compared with the actual angular position of each joint. The resulting position error signal is also subjected to a suitable "position control law" algorithm.

In order to exert the proper contact force against the object and to achieve a convenient exploratory movement along its surface, the results of the operations previously described are simply summed. We should point out that in the proposed control strategy the "predictions" made on the surface progress (that originate from the knowledge of the tangential direction in the actual contact point) are subjected to a correction at every sampling instant in the calculation cycle. It is this mechanism that allows us to speak about "inherent agreement" between commands and physical restraints.

The difference between the cases of tactile exploration and other robotic tasks requiring compliance is now evident: in the latter case, in fact, "predictions" (the position of the hole, the orientation of the table) cannot be tested and corrected directly, and other checking means (the aforementioned matrices) must be used.

Exploration with real tactile sensors. A real sensor does not possess infinite spatial resolution. This means that contact point and directions cannot be calculated exactly: the grosser the sensor resolution, the worse the performance of the proposed control method. For example, a typical PVF2 sensor we have developed has a density of about 1 sensor per 10 mm (however, the sensor we use in our present exploratory finger has a density even lower).

Furthermore complex sensor shapes (for instance sensors with double curvature and surface non developable on a plane, e.g. spherical) cannot be easily constructed using present technologies. The sensorized terminal link of our finger has cylindrical shape: hence exploratory motion requires some fingertip adaptation and the generality of the explored surface is unavoidably limited. Tactile exploration also implies inevitably friction effects between fingertip and object. A sensor able to detect also the tangential stresses originated during contact would be extremely useful and permit closer control of finger motion and finer manipulation.

Not even normal pressure reading is completely reliable in present tactile sensors. Poor linearity and significant hystheresis are some common drawbacks of most current sensors.

Thus, it is reasonable to suppose the performance of a reliable, and practically available, tactile sensor limited to the detection of bare on-off (contact-no contact) signals originated at each sensing site. Such an on-off sensor would provide only geometrical information on sensor-object contact; other transducing means should be used for the control of exerted forces.

A second control method, modified in order to mantain the peculiar features of the first we have proposed, but also to allow the use of a simple, binary type tactile sensor, has been therefore devised. A scheme of this second control method is given in Fig. 5.

According to this modified control method, the torque on each joint is calculated by multiplying the normal unit vector (provided by the binary force sensor) by the desired contact force intensity, and applying the result to the Jacobian transpose matrix. These torque goals are accomplished by four analogic servo loops, in which the desired torque is compared with a feedback signal provided by a strain-gauge-based transducing device (that measures the actual joint torque exerted by the actuating tendons). The error signal is then amplified, integrated and compensated in a conventional P.I.D. servo.

The use of the computer as a mere "target pointer" for the analogic actuating torque servo allows greater bandwidth of the servo itself, and decreases significantly the strain-gauge signal conversion and acquisition times in the computing cycle. In an alternative, possible configuration, the computer could also manage the torque feedback. However, the expected benefit provided by its versatility in compensating for torque control law would be probably nullified by the time-lag and inaccurancies introduced by the A/D conversion process. It should be pointed out that in this second version of the proposed method, the contact force control remains substantially "open-loop", as no means are provided for correcting errors made in computing the target torques.

IMPLEMENTATION AND DISCUSSION

The implementation of the concepts we have introduced above has been preliminary investigated by applying the method outlined for the case of a real tactile sensor to the control of the relatively simple robot finger shown in Fig. 1.

The finger has five links connected by 4 revolute joints, each actuated by a D.C. motor through a tendon-like cable and sheath system. The tactile sensor array is incorporated in the distal link of the finger. The control method is implemented in a DEC Micro PDP11/73 computer, interfaced to purposely designed hardware instrumentation.

The computations leading from the input (sensor signal vector and encoded position feedbacks) to the output (torque and position command signals) involve, for our 4 d.o.f. device, about 10 trascendental calls, 30 multiplies and 8 adds. The details of the computations are given in the Appendix.

Additional, rather short computation time is consumed by the above mentioned warning algorithm: the position constraints set by the higher level controller for each exploration phase are compared with the actual values. Torque limiting, instead, is carried out more reliably by hardware means. A short time is also consumed by addressing tactile and positional information storage; these data will be retrieved in the subsequent phases of path reconstruction and analysis (see Fig. 1). An extimated value for the sampling rate is 80Hz.

It should be pointed out that the solution for the positions and torques of joints is simple enough to be performed in real time only in a few particular cases: for most 6 d.o.f. manipulators, in fact, it is very difficult to invert symbolically the Jacobian matrix. Owing to the particular configuration of our finger, a symbolical inversion of the Jacobian matrix was possible. Computation times would have been much longer if numerical inversion of the matrix were necessary.

No compensation terms are provided for the dynamic effects of the structural inertia and masses, since fast motions are not required. On the contrary, Coulombian friction effects, which are high in the cable-and-sheath transmission system, heavily affect force control performances. By closing the torque control loop around the major friction sources, and superimposing a "dither" signal (a high-frequency vibration with null average value which eliminates "stick-slip" effects) smooth finger movements have been obtained.

At this time most components of our system have been realized and tested with satisfactory preliminary results.

APPENDIX

For our manipulator, the matrices referred to in the scheme of Fig. 5 are:

$$J^T = \begin{pmatrix} 0 & 0 & J_f & 1 \\ J_a & J_c & 0 & 1 \\ J_b & J_d & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (1)$$

$$J^{-1} = 1/J_e \begin{pmatrix} 0 & 0 & J_e/J_f & 0 \\ J_d & -J_b & 0 & J_b \\ -J_c & J_a & 0 & 0 \\ J_c-J_d & J_b-J_a & 0 & J_e \end{pmatrix} \qquad (2)$$

where:

$$\left| \begin{array}{l} J_a = L_3 S_4 + L_2 S_{34} \\ J_b = L_2 S_4 \\ J_c = L_3 C_4 + L_2 C_{34} \\ J_d = L_2 C_4 \\ J_f = -S_{234} \\ J_e = J_a J_d - J_b J_c \end{array} \right. \qquad (3)$$

and Li = lenght of the ith link

Sj(Cj) = sine (cosine) of the j-th joint angle

Sjk(l) = sine of the sum of j-th and k-th (and l-th) joint angles

It is appropriate to provide a brief explanation for the 4x4 sizeing of matrices (1) and (2).

In fact the original size of the Jacobian matrix is 4 (as the joints) x 6 (as the d.o.f. representing the general motion of the finger). Accordingly, possible fingertip movements must comply with the conditions given by the two following equations:

$$D_x = \frac{S_{234}}{C_{234}} D_y \qquad (4)$$

$$D_y = \frac{-C_{234}}{L_3 C_{23} + L_2 C_2 + L_1} \theta_z \qquad (5)$$

where: Dx, Dy are the motion components along x and y axes of the fingertip frame (see Fig. 3);

θ_z = rotation about z axis.

Whenever the desired motion is possible (equations (4) and (5) are verified), two raws of the Jacobian matrix are a linear combination of the remaining four and are then omitted.

The kinematic limitations of our 4 d.o.f. finger configuration can be partly overcome by selecting appropriate motion directions in the plane tangential to the object surface.

By developing the matrix notation used in the scheme of Fig. 5 we obtain the following expressions for joint torques (Ti) and angular displacements (dΘi):

$$\left|\begin{array}{l} T_1 = (J_g - J_m \zeta) P \cos\alpha \\ T_2 = (J_c - \zeta) P \sin\alpha \\ T_3 = (J_d - \zeta) P \sin\alpha \\ T_4 = \zeta P \sin\alpha \end{array}\right. \qquad (6)$$

$$\left|\begin{array}{l} d\theta_1 = -\dfrac{\sin\alpha}{J_g} D_s \\ d\theta_2 = -\dfrac{J_b}{J_h}\cos\alpha\ D_s \\ d\theta_3 = \dfrac{J_a}{J_h}\cos\alpha\ D_s \\ d\theta_4 = \dfrac{J_a - J_b}{J_h}\cos\alpha\ D_s \end{array}\right. \qquad (7)$$

where:

$J_g = L_3 C_{23} + L_2 C_2 + L_1$

$J_m = - C_{234}$

P and D_s = imposed normal force and lenght of exploratory step, respectively.

α and ζ define the sensor in contact with the object, as shown in Fig. 3.

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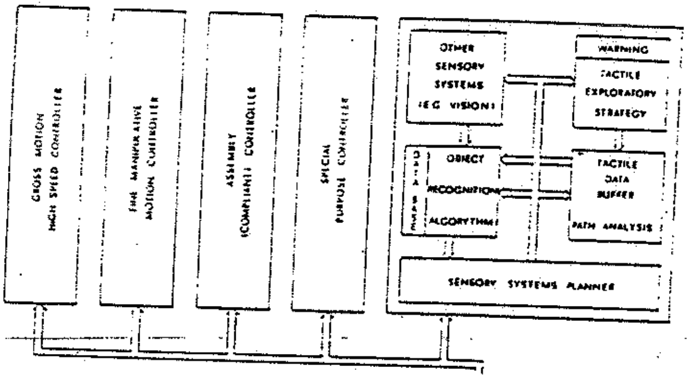

Fig. 1 An overall architecture for the proposed robot controller.

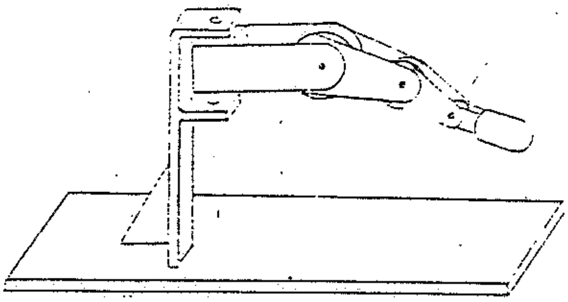

Fig. 2 The 4 degree-of-freedom, sensorized, exploratory finger.

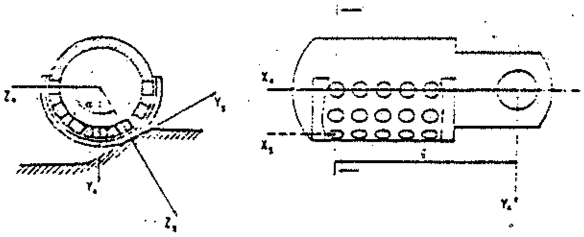

Fig. 3 Configuration of the sensorized fingertip with its compliance frame (Left: cross section; right: side view).

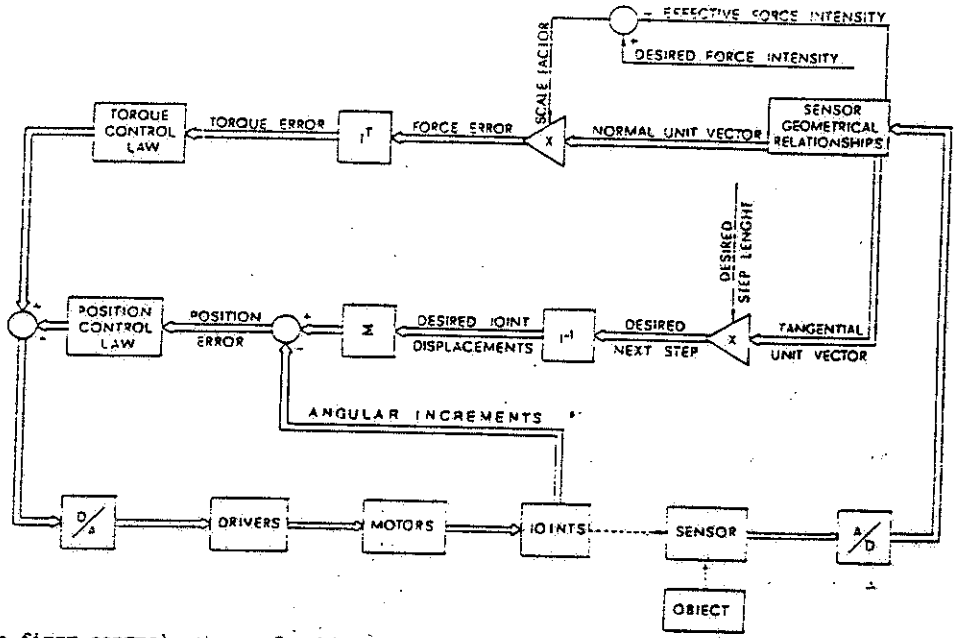

Fig. 4 The first control scheme. In this configuration tactile sensors provide analogic signals.

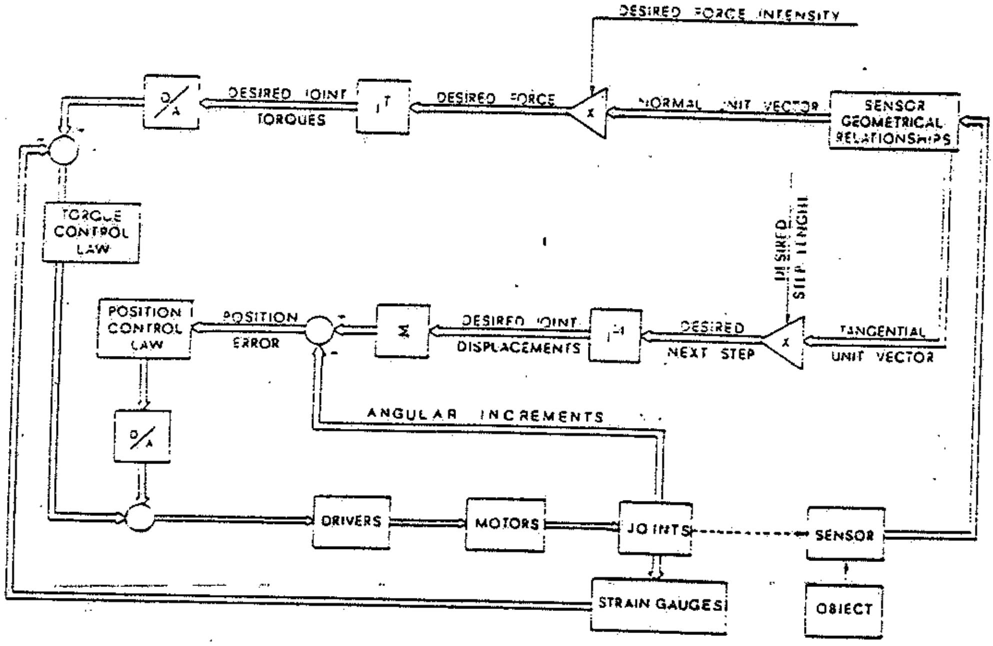

Fig. 5 The second control scheme. In this configuration tactile sensors operate in binary mode.