ADAPTIVE SURFACE FOLLOWING AND RECONSTRUCTION USING INTRINSIC TACTILE SENSING

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ABSTRACT

In this paper a method is described for automatically exploring unknown objects by means of a dextrous robotic hand, and for reconstructing the geometrical features of these surfaces. The method exploits the unique capabilities of Intrinsic Tactile sensing (ITs), in order to both execute hybrid (position/force) control of robot actions, and to acquire information about the explored surface. A brief description of ITs, i.e. contact sensing based on force/torque measurements at the hand's fingertips, is provided in the paper. A hybrid control scheme is discussed, which is capable of properly driving the sensorized fingertip during the exploration. The problem of reconstructing geometric features of the surface from sensory data is also addressed, and an algorithm for on-line estimation of surface parameters is proposed. Finally, an experimental verification of the proposed methods applied to a robotic hand equipped with IT sensors is presented.

1. INTRODUCTION

It is a wide-spread opinion that one of the most challenging tasks of advanced robotics is *dextrous* manipulation, which can be defined as the ability of a robot to perform operations on its environment comparable in complexity with those accomplished by human hands. Although some of the devices proposed in recent years (e.g. the dextrous hands of Stanford/JPL [1] and Utah/MIT [2]) have already succeeded in accomplishing rather sophisticated manipulations, it is widely recognized that further improvements will be possible under condition of intensive utilization of sensory devices, especially tactile ones.

The state of the art in tactile sensing is at present characterized by a rather deep distinction: on the one side are conventional devices, composed of many (hundreds) pressure sensitive elements placed in arrays on the fingertip surface; on the other, are the so-called "intrinsic" tactile sensors. Intrinsic Tactile (IT) sensing basically relies on the interpretation of contact geometries starting from force measurements [3], [4]. IT sensors are comprised of very simple elements: only a miniaturized six-axis force/torque sensor fixed to the fingertip is needed in order to infer many data useful for manipulation control. In comparison with conventional tactile devices, IT sensors lack the ability to provide information about the local pressure distribution over the contact area. On the other hand, IT sensing is able to provide very precise information about important geometric quantities and interactions at the contact, such as:

a)the position of the contact point on the fingertip surface (more precisely, IT sensors can give the location of the *contact centroid*, an important point whose properties are discussed in [5]);

b)the direction of the unit vector normal to the contacting surfaces;

c)the intensity and direction of the resultant contact force (comprised of both compression and friction components);

d)the intensity of the torque generated by friction forces.

Algorithms for IT sensing are presented in [5]. Implementations of IT sensors for sensorizing dextrous hands are discussed in [5], [6], [7]. A detailed analysis of advantages and drawbacks of conventional and intrinsic tactile sensing is reported in [8]. For their simplicity, fast response and unique information on friction forces, IT sensors result to be very suitable for manipulation control.

By using sensory feedback from the hand fingertips, fingers can be driven in the exploration of the surfaces of unknown objects. The goal of such exploration is the extraction of surface features that can be used during subsequent phases of the manipulation task: for instance, properties relating to the surface geometry, friction and material compliance can be obtained using IT sensing [5]. In this paper, the particularly interesting problem of geometric feature extraction will be approached, involving the direct measurement of some geometric parameters of the surface. Parameters can be either *local*, obtained through exploration of a small neighborhood of the contact point (e.g. the orientation of the tangent plane and the principal curvature radii), or proceed from wider sweep motions.

Based on such measurements, object classification can follow, and data can be integrated with other sensed properties of the object in order to perform automatic recognition of objects. The geometric characterization of objects can be usefully applied also to the analysis of grasp stability and to manipulation planning.

Problems involved in sensory-based exploration of objects are basically two: i)how to realize smooth motions of the fingertips in contact with the object surface, either by slipping or rolling on it, and ii)how to reconstruct surface shape from sensory data. These problems are discussed in sect.2 and 3, respectively; in sect.4, some preliminary experimental results are presented.

2. HYBRID CONTROL OF TACTILE EXPLORATION

In order to carry out tactile exploration, the fingertips of the robot hand must follow the object surface, while a proper contact force is maintained between the fingers and the object. In fact, experiments of tactile exploration without continuous control of the contact force have been already presented in literature: for instance, both Allen [9] (using a conventional tactile sensor) and Brock [6] (using an IT one) realized tactile exploration of object based on probe-withdraw motions. However, continuous control of contact force is mandatory for example when, concurrently with the exploration, the hand is also expected to mantain a stable grasp on the object. Moreover, finer information about the object surface can be elicited in this way.

Continuous following of unknown surfaces has been performed by several researchers in the recent past. For example, Cutkosky [10] presented an application to surface finishing of a robot equipped with a force/torque sensorized wrist. Montana [11] discussed a method for contour following employing sensorial feedback from a planar tactile sensor. In this paper, a method is presented which significantly simplifies the control of tactile exploration, by exploiting the characteristics of intrinsic tactile sensors.

Fig.1 depicts three fingertips of a robot hand grasping an object of unknown shape; one of the fingertips is moving to explore a portion of the object surface. Consider a reference frame C_xyz with origin at the contact centroid and the C_z axis parallel to the outward-pointing normal direction to the fingertip surface at C. While a force control loop must be implemented along the z axis in order to follow the desired normal force trajectory (most often a constant value), the position of the finger relative to the surface must be controlled along the x and y directions, as well as the rotations of the fingertip about each axis. According to Paul [12], the C_xyz frame represents the "constraint" frame for the exploration task. It should be noted that, as the exploration proceeds, the contact centroid moves across the contacting surfaces, and the constraints frame varies as well. By using IT information and the direct kinematic relationships of the finger, the constraint frame can be instantaneously located w.r.t a fixed base frame.

An hybrid (force/position) controller capable of realizing the above described task can be obtained by summing at the leads of the finger actuators two sets of inputs, respectively pertaining to force and position control along orthogonal directions in the constraint space. The generation of such inputs is briefly examined in the following.

[1] The hypothesis is made here that exploratory motions start when the fingertip is already in touch with the object.

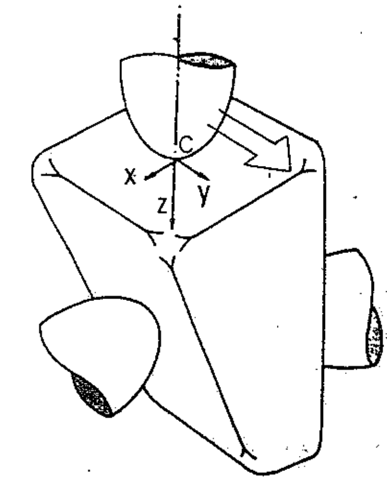

Fig.1: *Three fingertips of a robot hand grasping and exploring an unknown object.*

Normal force control

The control of the normal component of contact force between the fingertip and the object is of the foremost importance in exploration tasks, since it involves the integrity of the (possibly fragile) object and sensorized fingertip, and affects the stability of the grasp. A possible control scheme for normal force control exploiting IT information is depicted in fig.2[1].

The vector $\mathbf{f}_c = (f_x\ f_y\ f_z\ q\ 0\ 0)^T$ of contact force/torque applied between the two surfaces, and the direction of the unit vector $\mathbf{n} = (n_x\ n_y\ n_z\ 0\ 0\ 0)^T$ normal to the surfaces at the contact centroid, result from IT measurements (note that $\mathbf{n}$ is here the generalization to $\Re^6$ of the three-dimensional normal unit vector, $\mathbf{n}' = (n_x\ n_y\ n_z)^T$). The intensity f_n of the normal component of contact force is easily calculated as $f_n = \mathbf{f}_c^T\,\mathbf{n}$. The error between the desired and sensed values of normal force in the constraint frame, $\mathbf{e}_n = (f_d - f_n)\,\mathbf{n}$, is transformed in the corresponding vector in the joint torque space through multiplication by the finger transpose Jacobian matrix:

$$\mathbf{e}_t = \mathbf{J}^T\,\mathbf{e}_n \qquad (1)$$

The commanded torques to joint actuators τ_n are chosen according to the law:

$$\tau_n = f_d\,\mathbf{J}^T\,\mathbf{n} + \mathbf{K}_p\,\mathbf{e}_t + \mathbf{K}_I \int \mathbf{e}_t\,dt + \mathbf{K}_d\,\dot{\mathbf{e}}_t \qquad (2)$$

where $\mathbf{K}_p$, $\mathbf{K}_I$, $\mathbf{K}_d$ are positive definite constant matrices, corresponding to proportional, integral and derivative gains respectively. Eq.2 is an example of PID-plus-feedforward force control law, and it can be easily shown to steer $\mathbf{e}_t$ to zero. This will also guarantee the convergence of the normal component of contact force f_n to the desired value f_d.

Position control in the tangent plane.

Small motions of the fingertip along the object surface can be represented by any combination of the 5 positional degrees of freedom in the constraint frame. Translations along the C_x and C_y axes involve slipping between the surfaces, while rotations about C_x and

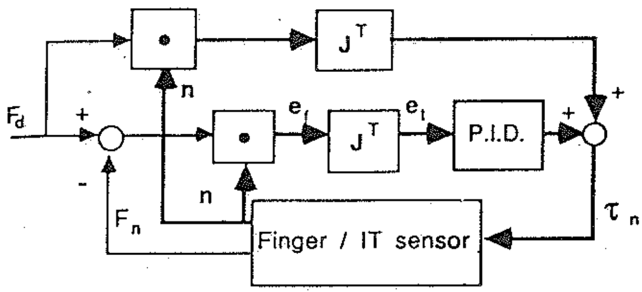

Fig.2: *Normal force control loop.*

C_y are obtained through rolling the fingertip on the object, and a rotation about the C_z axis involves a "spinning" relative motion.

Any small position/rotation vector δ (in the constraint frame) which is orthogonal to **n** is therefore a possible exploratory motion. The choice of the direction of δ is arbitrary to the extent that is allowed by the finger kinematic capabilities: good choices of δ are those which permit to gather the maximum information about the investigated geometric parameters of the surface.

In the joint space, a motion of δ corresponds to joint motions $\underline{\delta}_q$ given by:

$$\delta_q = J^{-1}\,\delta \tag{3}$$

A PID control law can be applied to generate joint torques τ_n so that the fingertip is constrained to track the desired exploratory trajectory:

$$\tau_q = K'_p\,\delta_q + K'_i \int \delta_q\,dt + K'_d\,\dot{\delta}_q \tag{4}$$

In the presence of friction, stick-slip is one of the main obstacles to a smooth control of the sliding of objects. This phenomenon consists of unstable motions with sudden stops and accelerations, resulting from the coupled effects of finger elasticity and stiction between surfaces. The peculiar capability of IT sensors to measure the friction components of contact force and torque opposing to smooth exploratory motions, can be used to compensate for these effects. In fact, the joint torques necessary to equilibrate friction force $\mathbf{f}_f$ are given by:

$$\tau_f = J^T f_f = J^T\,[f_c - (f_c^T n)\,n] \tag{5}$$

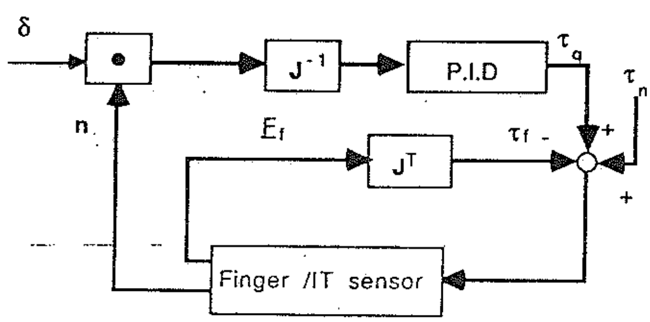

Fig.3: *The hybrid controller for tactile exploration using IT sensing. Normal force restoring torques τ_n are synthesized by the controller in fig.2.*

In principle, cancellation of the effects of friction would be possible by commanding to the finger actuators the friction compensating torques τ_f, in addition to the normal force restoring torques τ_n and to position control torques τ_q (see fig.3). However, perfect compensation can not be achieved, due to the finite stiffness of the links connecting finger actuators to the fingertip.

3. SURFACE RECONSTRUCTION ALGORITHM

In order to reconstruct the characteristics of the object surface being explored and render it possible to use such information in further manipulative operations on the same object, the large amount of data collected during exploration (specifically, a set of points belonging to the explored surface and the corresponding normal unit vectors) must be processed and reduced to a more compact form. Montana [11] proposed a method to infer punctual characteristic of the explored surface (namely, the 2x2 matrix of surface curvatures form at the explored point) starting from tactile data. Although the method is elegant, and the information provided very useful for manipulation control, it seems that results are too prone to sensor noise and other errors in the system. Fitting the collected points with large patches of geometrical surfaces can provide a more robust way of compressing tactile data. Allen [9] used bicubic surface patches to fit data from two CCD cameras and used tactile sensing to disambiguate features like concavity-convexity. In both Montana and Allen works, surface characteristic extraction can only be performed off-line, at the end of the exploration phase.

In the following, we will describe an algorithm for fitting tactile data with a quadratic surface, and show that estimates of the surface parameters can be updated at each exploration step asymptotically converging to the actual values of the fitting surface.

If the explored surface is approximated with a quadratic form, it can be described in a general reference frame choosen to be the "base" frame by the implicit equation:

$$S(r) = r^T Q r + 2 p^T r - 1 = 0 \tag{6}$$

where $Q \in \Re^{3\times3}$, $Q = Q^T$, $p \in \Re^3$, and r describes a generic point in $\Re^3$.

The information available at each exploration step consists of: i) the contact centroid location, $c = (x\ y\ z)^T$; ii) the unit vector normal to the surfaces at c, $n' = (n_x\ n_y\ n_z)^T$. Both C and n can be obtained through the use of IT sensing, and expressed in terms of the base frame using the direct kinematic relationship of the exploring finger. The following equations can be written:

$$c^T Q\, c + 2\, p^T c = 1 \tag{7}$$

$$2\, Q\, c + 2\, p + k\, n' = 0 \tag{8}$$

respectively stating that the detected point c belongs to the quadratic surface S, and that the gradient of S at c is parallel to the detected normal n'. Eq.7 and 8 form a linear system of 4 scalar equations in 10 unknowns (6 elements q_{ij} of Q, 3 elements p_i of p, and the gradient magnitude k), which can be rewritten as:

$$y = W a \qquad (9)$$

where $a = (q_{11}\ q_{22}\ q_{33}\ q_{12}\ q_{23}\ q_{13}\ p_1\ p_2\ p_3\ k)^T$ is the unknown surface parameter vector, $y = (1\ 0\ 0\ 0)^T$, and the coefficient matrix is given by:

$$W = \begin{bmatrix} x^2 & y^2 & z^2 & 2xy & 2yz & 2xz & 2x & 2y & 2z & 0 \\ x & 0 & 0 & y & 0 & z & 1 & 0 & 0 & n_x \\ 0 & y & 0 & x & z & 0 & 0 & 1 & 0 & n_y \\ 0 & 0 & z & 0 & y & x & 0 & 0 & 1 & n_z \end{bmatrix}$$

Since eq.9 is underdetermined, at least three points on the surface must be detected to solve for the unknown parameters. By gathering data from n exploratory motions, an over-determined linear system of 4n equations in 10 unknowns could be formed, and the unknown parameters could be evaluated by using e.g. least-squares approximation techniques. However, this method is subject to amplification of errors in data measurement. In fact, the coefficient matrix W' formed by stacking the W's obtained from each measurement, may easily be ill-conditioned if measurements are taken at points close to each other; and, unfortunately, least-squares problems are particularly sensitive to ill-conditioning [13].

As an alternative to the algebraic solution of eq.9, the problem can be reformulated in dynamic terms, so that the parameters are continuously estimated through an adaptive control algorithm. If $\underline{a}_{(k)}$ is the estimate of the parameter vector a after the k^{th} exploration step, a prediction error vector $e_{(k)}$ can be obtained as:

$$e_{(k)} = \underline{y}_{(k)} - y = W\,\underline{a}_{(k)} - W\,a \qquad (10)$$

An estimator algorithm can be designed having the form:

$$\underline{a}_{(k+1)} - \underline{a}_{(k)} = - P_{(k)}\, W^T e_{(k)} \qquad (11)$$

where $P_{(k)}$ is a positive definite gain matrix. The asymptotic convergence of the algorithm to the actual parameter values can be discussed using the Lyapunov function:

$$V_{(k)} = (\underline{a}_{(k)} - a_{(k)})^T (\underline{a}_{(k)} - a_{(k)}) \qquad (12)$$

By substituting eq.11 we have:

$$V_{(k+1)} - V_{(k)} = (\underline{a}_{(k)} - a_{(k)})^T (B^T B - I)(\underline{a}_{(k)} - a_{(k)}) \qquad (13)$$

where $B = I - P_{(k)} W^T W$. Different characteristics of the estimator algorithm result from different gain matrices, as discussed (for the continue time domain) by Li and Slotine [14]. Choosing $P_{(k)} = c_{(k)}\, I$, which involves $B = B^T$, it can be easily verified that $\|B\| \le 1$ for $0 < c_{(k)} < 2 / \lambda_{max}(W^T W)$. Therefore, for such c's, we can write:

$$V_{(k+1)} - V_{(k)} \le (\|B\|^2 - 1)\, \|\underline{a}_{(k)} - a_{(k)}\|^2 \le 0 \qquad (14)$$

In order to avoid the computation of the eigenvalues of $W^T W$, he scalar gain factor $c_{(k)}$ can be chosen as:

$$c_{(k)} = 2 / \mathrm{trace}\,(W W^T) \qquad (15)$$

which can be easily computed at each exploration step.

The condition for persistent excitation usually needed in adaptive control theory is easily seen to correspond to non trivial trajectories of the fingertip on the object surface. This can be achieved by a suitable choice of the direction of the position input vector δ (see sect.2). In the exploratory phase it is possible, in principle, to improve the convergence characteristics of the recognition algorithms going from a rough description of the local properties of the surface to a finer one, through a betterment process; such learning procedures will be the subject of subsequent investigations.

4. EXPERIMENTAL RESULTS

The above-described method for the exploration of the surfaces of unknown objects has been experimentally verified using a three-finger articulated hand (Stanford/JPL hand, [1]) equipped with an intrinsic tactile sensor on the "thumb".

In a preliminary verification phase, experiments have been carried out as follows:

1)objects of different shape and material are firmly grasped between two fingers. Only joint position and torque sensors are used in this phase;
2)the sensorized thumb is moved towards the object slowly, touches its surface and presses it until the normal component of contact force (read by the IT sensor) reaches a desired value;
3)the thumb fingertip starts moving with respect to the object, while mantaining the desired value of normal contact force, according to the control scheme described in sect.2;
4)tactile data are stored while exploration goes on.

With reference to the simple planar exploratory motion depicted in fig.4, the Jacobian matrix relating motions in the constraint frame C-yz with joint angles, employed in the relationships of sect.2, is:

$$J = \begin{bmatrix} -aS_1-(b+z_c)S_{12}-y_cC_{12} & -(b+z_c)S_{12}-y_cC_{12} \\ aC_1+(b+z_c)C_{12}+y_cS_{12} & (b+z_c)C_{12}+y_cS_{12} \end{bmatrix}$$

where: S_1, S_{12}, C_1, C_{12} stand for the sine and cosine of joint angles θ_1 and θ_2, respectively; a, b are the lengths of the finger links; and y_c, z_c are the contact centroid coordinates measured in a reference frame fixed with the IT sensor at the base of the fingertip, S-yz. The unit vector normal to the surfaces at the contact centroid in base frame coordinates is: $n = (n_y, n_z)^T = (z_cC_{12}-y_cS_{12}\ ,\ z_cS_{12}+y_cC_{12})^T$.

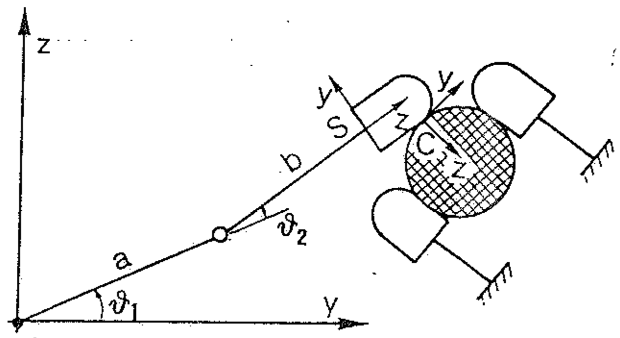

Fig.4: *Exploration of the surface of a cylindrical object of unknown diameter.*

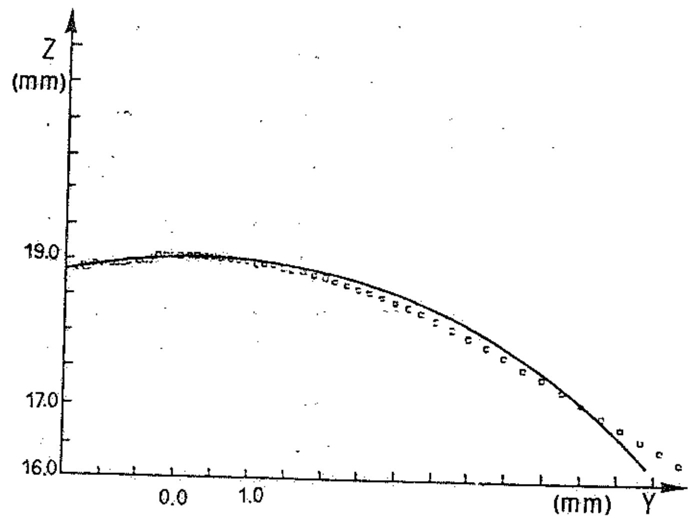

Fig.5: *Reconstruction of the cross section of a cylindrical object.*

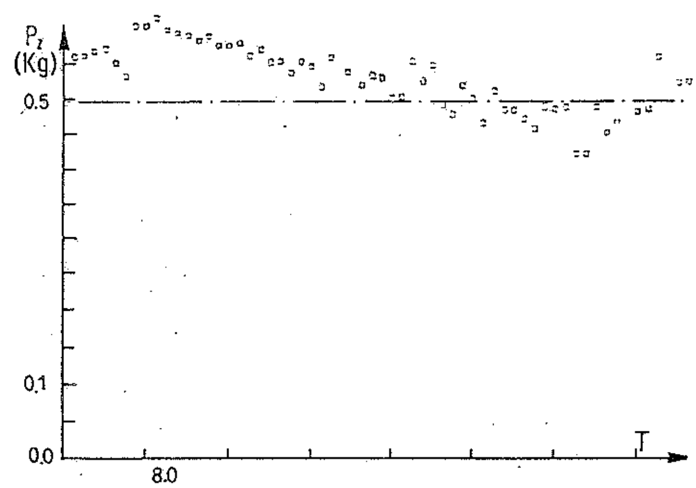

Fig.6: *Normal force oscillations during exploration. Dashed line corresponds to the desired value.*

Contact centroid coordinates in the base frame, obtained during the exploration of a cylindrical object (38 mm diameter), are plotted in fig.5. A solid line contour, corresponding to the actual shape of the object in the cross section being explored, is superposed to experimental data for reference.

The measured intensity of the normal component of the contact force is plotted versus time in fig.6

Similar exploration experiments have been carried out with 5 cylindrical objects having diameters ranging between 40 and 100 mm. Curvature radii could be detected with errors less than 5 mm.

Further experiments are currently being undertaken in order to evaluate the effectiveness of the friction compensation method of sect.2, and the reconstruction algorithm discussed in sect.3.

CONCLUSIONS

A method for controlling the exploration of the surfaces of unknown objects using articulated hands has been discussed in this paper. The hybrid control scheme capitalizes on information provided by "intrinsic" tactile sensors situated in the hand's fingertips. An algorithm for estimating explored surface parameters during exploration has also been proposed. Experiments validating the proposed control scheme are presented.

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