# AUGMENTATION OF GRASP ROBUSTNESS USING INTRINSIC TACTILE SENSING

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**ABSTRACT**. *In this paper we will discuss one of the possible applications of Intrinsic Tactile sensing (ITs) to grasp and manipulation control. A brief description of ITs , i.e. contact sensing based on force/torque measurements at the hand's fingertips, is provided in the introduction. A new method for using sensory feedback in the control of grasp forces to augment grasp robustness against slippage, is discussed with respect to a simple grasp type; simulation and experimental data are provided. The possible generalization of this sensor-driven approach to the control of optimal grasp force in complex grasp configurations is addressed, even though much work has still to be done to integrate the results of classical work on grasp synthesis with real-time information on contact offered by ITs.*

## 1. INTRODUCTION

Dextrous manipulation, the ability of a robot manipulator to perform operations on its environment which are comparable in complexity to those accomplished by human hands, can be subdivided in three main parts: grasp, micro-movement and tactile exploration. Although some of the dextrous hands proposed in recent years (e.g. [Salisbury,82], [Jacobsen,84]) have accomplished to some extent those goals, it is widely recognized that further improvements will be possible under condition of intensive utilization of sensory devices, especially tactile ones.

In this paper we will discuss a method for exploiting the potential of contact sensing devices based on the "intrinsic" approach, in order to enhance the ability of a dextrous hand to securely grasp an object, accurately control grasping forces and adapt them to external disturbances, so as to increase the robustness of the hold against slippage.

**Intrinsic Tactile sensing**. With the term "Intrinsic Tactile" sensing (ITs) [Bicchi,87] we refer to a contact sensing method utilizing the measurement of the force and torque resultant vectors generated by the distributed contact pressure acting between two touching bodies, as originally proposed by [Salisbury,84a]. An IT sensor is usually comprised of a 6-axis force/torque sensor built in the interior part of the fingertip of the robot end effector; the fingertip surface is not sensorized, and can therefore be realized in whatever shape and material the hand designer prefers.

As shown in [Bicchi,89], an ITs is able to completely characterize a soft-finger type contact, i.e. to find:

a)the position of the contact centroid (a point always belonging to the interior of the contact area) on the fingertip surface,
b)the intensity of the normal component of the contact force,
c)the intensity and direction of the tangential (friction) component of the contact force, and
d)the intensity of the torque generated by friction forces.

Moreover, if the fingertip surface is ellipsoidal (and in particular spherical, cylindrical or plane), that information can be obtained with a very simple and fast closed-form algorithm.

IT sensors obviously lack the ability to provide information about the actual shape of contact area. This is a minor problem whenever non-conformal surfaces are touching, since the contact area in this case is known to be approximated by a small ellipse; such is most often the case in normal operations of dextrous hands. Conformal-surface contacts do occur frequently with planar fingers: the possible integration of IT and conventional array-type tactile sensing in the plane fingers of a parallel-jaw gripper is discussed in [Bicchi,88]. Implementations of ITs for sensorizing dextrous hands are discussed in [Brock,85] and [Bicchi,87].

**Background on grasp**. The grasp of a robot end-effector (of any type, from grippers to dextrous hands) on an object can be described in terms of the number and the position of contacts between hand's fingers and the object and the intensity and direction of forces and torques exerted through contact. The synthesis of a grasp consists therefore of two basic phases: a) locating the fingers relative to the object, and b) determining the forces and torques to be exerted at each contact. To both of these questions different answers are possible, depending upon the degree of determinism in the approach followed.

An example of fully deterministic planning of grasp geometry , i.e. planning based on the assumption that all data (shape and orientation of the object, friction characteristics etc.) are available *a priori* with high precision, has been presented by [Nguyen,86]. His method allows one to synthesize grasps of polyhedral objects with multifingered hands, in such a way that the grasps are *stable* (in the sense that the hand-object system returns to equilibrium configuration if slightly perturbed) and *force-closure* (i.e. capable of equilibrating any external force tending to move the object, provided that arbitrarily large grasping forces can be exerted).

An example of a non deterministic approach to grasp geometry synthesis is the "reflex control" method of [Tomovic,86]: *a priori* information on the task are only approximate, and the grasp is built on the basis of sensory feedback and system experience.

Once the relative positions of the object and the fingers is fixed, the contact force at each contact has to be determined; those forces are of course a function of the external forces acting on the object which must be resisted by the grasp. However, as shown e.g. by [Salisbury,82], in most cases the constraints to object motion are redundant, so that this function is not one-to-one. In other words, for a given grasp geometry, there exist in general infinite possible combinations of contact forces and torques balancing given external forces; the effect of



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different grasp force systems is only to generate different *internal* forces, modifying the object's internal stress state. As a consequence, there is the possibility to choose, among the infinite possible systems of contact forces, the one which is best according to some optimality criterion.

The choice of such criteria can be made on the basis of considerations such as:

a)The contact forces and torques generated by friction must comply with limitations given by Coulomb's law (for forces) or by its generalization (cf. [Howe,88] and a following section). The further the contact conditions are from slippage danger, the more robust is the grasp;

b)The stresses due to contact forces must be smaller than the maximum allowable for the object and the finger, in order to avoid their damage;

c)In certain cases, contact forces must be mantained at a minimum level, even if that is not required by the equilibrium of the object, to guarantee the continuity of contacts over time;

d)The torques of the hand actuators required to exert the specified contact forces must not overcome their hardware limits. In order to increase the efficiency and accuracy of force control, it is rather advisible to mantain those torques at the lowest possible value. This specification is in practice reflected on contact forces themselves.

Also possible approaches to the optimal choice of contact forces and torques can be more or less deterministic. A very elegant example of optimal internal forces determination in grasps with precisely defined geometry and external loading has been given by [Kerr,86]. A method to define optimal grasp forces in grasps with known geometry but with external loading variable in a limited range has been presented by [Yoshikawa,88]; an algorithm for determining optimal contact position and forces on grasped objects of known geometry in the planar case, is discussed in [Bologni,88].

These and other methods proposed so far provide analytic and synthetic methodologies which are fundamental to the understanding of the optimal grasp problem. From an operative point of view, though, they require precise *a priori* information which are seldom available in practice; and this accuracy is even harder to achieve if the robot is to be operated in unstructured enviroments, such as those expected for advanced robotic applications.

Consider for example a grasp realized, in its initial phase, by a reflex type strategy: the shape of the object and the position of the fingers on it are known only approximately, so that any of the aforementioned methods to choose grasp forces are not reliable. Moreover, external loadings disturbing the grasp during robot operations are also largely indeterminate. In such cases the potential usefulness of hand control methods capable of automatically imposing optimal contact forces and adapting them in real-time to variations of external loading is quite apparent.

Probably because of the lack of sensing devices suitable for such task, this approach to grasp control has not been followed so far (at least as far as we know). In the following we will discuss how an IT sensor can be effectively utilized to optimize grasp forces in an adaptive fashion.

## 2. SIMPLE PLANAR GRASP

In order to introduce the approach to grasp force control we propose, we will consider in this paragraph the extremely simplified case of 2D grasp sketched in fig.1:

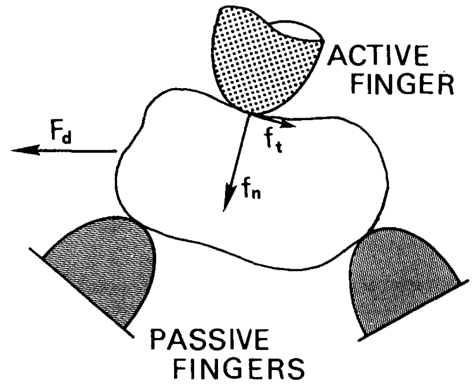


**FIG.1:** *Planar grasp with one active finger.*

A general shape object is held in a grasp comprised of some (at least 2) contacts with fingers. Among the fingers, only one is supposed active, i.e. equipped with an IT sensor and capable of independent actuation; passive fingers are considered as unmodifiable static constraints. The object is also subject to the external force $\underline{F}_d$ disturbing the grasp stability. The intensities of the tangential and normal components of the active contact force are designed with $f_t$ and $f_n$; their ratio (friction ratio $R_f$) must be, according to Coulomb's law, less than or equal to the static friction coefficient $\mu_s$ relative to the finger-object contact. We assume the value of $\mu_s$ to be known with some approximation. A method for direct measurement of friction coefficients using IT sensing on articulated hands has been discussed in [Bicchi,89], and can be easily realized in practice.

The goal of this method is to find the optimal normal force $f_n$ to be imposed by the active finger on the object, in order to comply with variations of external force $\underline{F}_d$ (and consequent variations of the friction component of contact force $f_t$). It should be pointed out that, for simplicity's sake, we assume here that $f_t$ has no effect on the internal forces in the grasp.

The aforementioned considerations on optimality criteria can be illustrated with reference to fig.2:

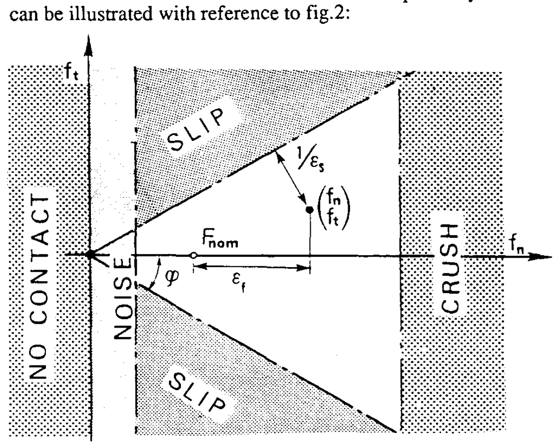


**FIG.2:** *Unacceptable contact conditions in* $f_n$-$f_t$ *plane*

In this figure the portions of the $f_n$-$f_t$ plane in which contact conditions are not acceptable for different reasons are apparent. For the correct utilization of the sensor, it is useful to mantain the normal component of contact force over a low threshold, so that signals can be discriminated from electrical noise. On the other hand, the normal force cannot exceed a limit value, $F_{crush}$, corresponding to limitations on object/fingers strength and/or on actuators performances. The portions of the plane external to the angle $\phi = \mathrm{artg}\ \mu_s$ correspond to friction ratios higher than $\mu_s$, i.e. to slippage. Finally, a nominal value $F_{nom}$ for normal force is given, representing the desirable value of $f_n$ in absence of disturbances: $F_{nom}$ can be for instance the result of one of the said grasp synthesis methods.

The target of normal force control is then twofold:
- $f_n$ should be mantained as close as possible to $F_{nom}$;
- the distance of the point $(f_n,f_t)^T$ (representing current contact conditions) from the boundary of slippage region should be as large as possible.

These conditions can be expressed mathematically by the minimization of the two terms:

$$\varepsilon_f = | f_n - F_{nom} | \tag{1}$$

$$\varepsilon_s = \frac{\sqrt{\mu_s^2 + 1}}{|\mu_s f_n - f_t|} \tag{2}$$

(the second term is the inverse of the said distance).

If positive weights $\alpha$, $\beta$ are assigned to those terms, we can consider a global error figure:

$$\varepsilon = \varepsilon(f_n) = \alpha\, \varepsilon_f + \beta\, \varepsilon_s \tag{3}$$

We will consider optimal the normal force that minimizes the error $\varepsilon(f_n)$ while satisfying all the constraints in the $f_n$ - $f_t$ plane.

In fig.3 is qualitatively illustrated the shape of $\varepsilon(f_n)$ for some values of $f_t$, $\mu_s$, $\alpha$, $\beta$:

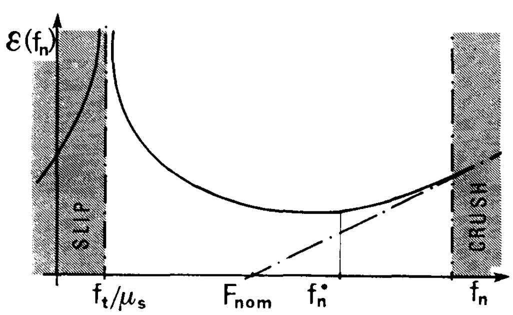


**FIG.3:** *The global error figure* $\varepsilon(f_n)$ *as a function of* $f_n$

It can be easily verified that $\varepsilon(f_n)$ has a minimum corresponding to the normal force value:

$$f_n^* = \max \left\{ F_{nom}, \frac{f_t}{\mu_s} + \frac{\sqrt{\beta}}{\sqrt{\alpha}} \frac{1}{\sqrt{\sin \phi}} \right\} \tag{4}$$

As a result, the optimal value of $f_n$, at varying the tangential component $f_t$ (which is measured by the IT sensor), follows the trajectory:

$$f_n^\wedge = \min \left\{ F_{crush}, f_n^* \right\} \tag{5}$$

The weights $\alpha$, $\beta$, or rather their ratio $\alpha/\beta$, represent an estimate on the dependability of the assumed friction coefficient. In fact, consider the particular cases:

a) $\beta = 0$, $\alpha \neq 0$; the optimal trajectory $f_n^\wedge$ at varying $f_t$ is described in fig.4.a:

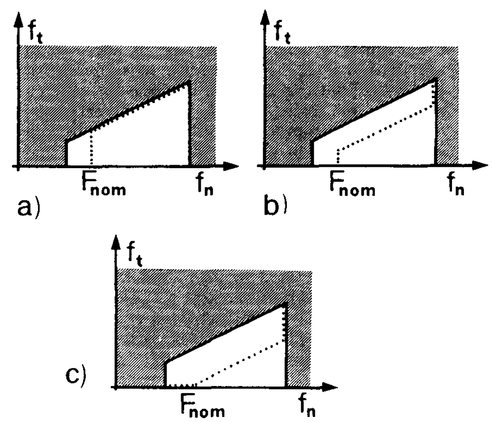


**FIG.4:** *Optimal trajectories of normal contact force for three different dependability figures* $\beta / \alpha$

which indicates as the dependability of $\mu_s$ is assumed infinite.

b) $\alpha/\beta > (F^2_{nom} \sin\phi)^{-1}$ (fig.4.b); the trajectory $f_n^\wedge$ is conservatively mantained in this case at a distance $\sqrt{\beta}\ \sqrt{\sin\phi}$ from slippage region.

c) $\alpha/\beta < (F^2_{nom} \sin\phi)^{-1}$ (fig.4.c); an even more pessimistic estimate of friction coefficient dependability leads to a trajectory that does not contain the desirable normal force at rest $F_{nom}$.

### 3. GENERALIZATION TO 3D

For a 3D grasp like the one showed in fig.5, distributed friction forces acting between the finger and the object are equivalent, in general, to two tangential components $f_{tx}$, $f_{ty}$ and to a torque m lying in the plane tangent to the touching bodies at the contact centroid.

In this case, the simple Coulomb's law has to be replaced by the inequality:

$$S\ (f_n, f_{tx}, f_{ty}, m) \leq 0 \tag{6}$$

where $S(\cdot)$ is a function whose description can be given in terms of the elastic, geometric and frictional parameters of the bodies.

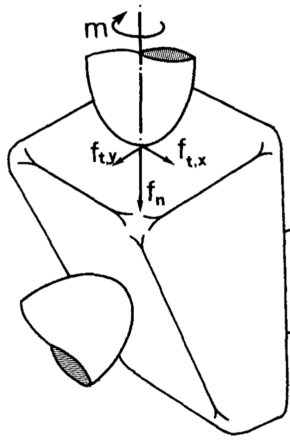


**FIG.5:** *Resultant friction force and torque in a 3D grasp.*

Eq.6 represents the region in the 4D space of load components where slippage does not occur. The surface $S(\cdot) = 0$ is called Limit Surface; the study of its properties for planar contacts has been approached e.g. by [Goyal,88]. A method for evaluating planar contact stability under combined load using an integrated tactile sensor (intrinsic + piezoelectric array tactile sensors) has been discussed in [Bicchi,88]; an iterative solution of a 2 by 2 nonlinear equations system resulted necessary.

However, exact methods for studing slippage under general loading are too complex to be used in real-time control of grasp. We will make therefore assumptions to obtain a simplified but conservative model of slip in 3D.

Consider first the case $m = 0$; Coulomb's law can be rewritten:

$$f_t = \sqrt{f^2_{tx} + f^2_{ty}} \leq \mu_s f_n \qquad (7)$$

In the opposite limit case, i.e. $f_t = 0$, the limit torque that can be resisted by friction forces depends not only on the normal component of contact force, but also on the shape of contact area. If geometric and elastic properties of the bodies satisfy the hypotheses of Hertzian theory on contact mechanics, contact area has an elliptical shape and extension increasing with the increase of $f_n$. This indicates that the dependence of limit friction torque upon the normal force is more than proportional; this has been shown for spherical bodies in contact by [Jameson,85], who gives the relation:

$$m \leq K f_n^{4/3} \qquad (8)$$

where K is a function of the parameters of the objects. It should be pointed out that the hypotheses above are fairly well satisfied if curved fingertips are used, while it is not for the jaws of a planar gripper.

To further simplify the mathematics, we will adopt a linear approximation of eq.8:

$$m \leq K' f_n \qquad (8')$$

where K' will be chosen conservatively.

For the general case of combined load, we will assume that the contact area is symmetrical around the contact normal, so that only consideration of the resultant tangent force $f_t$ is needed; a slippage-safe region can be defined by the relation:

$$\mu_s m + K' f_t \leq K' \mu_s f_n \qquad (9)$$

which is illustrated in fig.6.

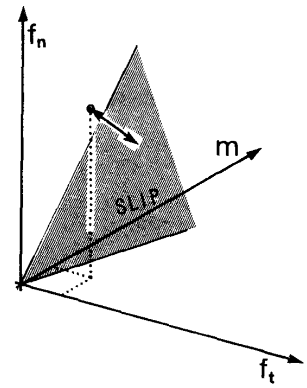


**FIG.6:** *The slippage-safe region for a 3D grasp.*

It should be noted that this approximation is similar to that proposed and experimentally verified by [Howe,88].

The inverse of the distance from slippage boundary of a contact where measured load components are $f_n$, $f_t$, m, is therefore:

$$\varepsilon_s = \frac{\sqrt{K'^2 + \mu_s^2 + K'^2 \mu_s^2}}{|K' \mu_s f_n - \mu_s m - K' f_t|} \qquad (10)$$

This value can be substituted in eq.3 so that the optimal value of $f_n$ corresponding to current values of $f_t$, m, is given by:

$$f_n\hat{} = \min \left\{ F_{crush}, f_n^* \right\} \qquad (11)$$

where:

$$f_n^* = \max \left\{ F_{nom}, \frac{f_t}{\mu_s} + \frac{m}{K'} + \frac{\sqrt{\beta}}{\sqrt{\alpha}} + \frac{\sqrt[4]{K'^2 + \mu_s^2 + K'^2 m_s^2}}{\sqrt{K' \mu_s}} \right\} \qquad (12)$$

We considered so far only one active finger controlling the grasp. Even if this is reasonable in some cases (e.g. if other fingers have much higher friction coefficients than the sensorized one, as discussed below), there are indeed further improvements of grasp robustness that could be accomplished with sensorization and actuation of more fingers. Moreover, in the general case, also tangential components of contact force and contact torque might have effect on the internal forces of grasp (more formally, might lie in the null-space of the grip transform); therefore, also the capability of fingers to control forces and torques in the contact plane should be considered.

An intuitive target for such multi-fingered grasp control is to minimize the maximum value of the error figure given by eq.3 and eq.11 for each active finger. Possible means to obtain this are:

a) increase the normal force of the worst-case finger;

b) increase the share of external load resisted by friction forces on the fingers having better error figures.

However, the problem is complicated by the complex interactions occurring among the control of individual contact forces and torques. A good deal of theoretical and experimental work is still needed to integrate the results of previous analytical methods for grasp analysis and synthesis with the newly available sensing techniques in such a general case.

## 4. SIMULATION AND EXPERIMENTAL RESULTS

In order to verify methods proposed in section 2, we carried out both numerical simulation and experimental tests.

***Simulation.*** Fig.7 shows the simple system used to model the active finger - object dynamics.

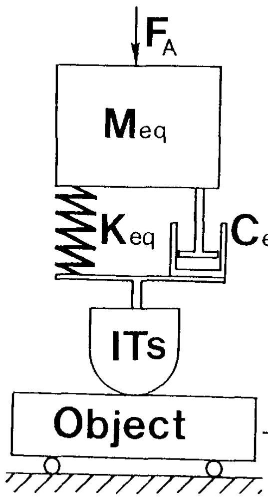


**FIG.7:** *Simulation model for the active finger - object system.*

All the masses of actuators, mechanical transmission and fingers, reduced to the actuator axis, are concentrated in a single equivalent mass; analogously are defined an equivalent elasticity and damping. The control of the normal component of contact force is made by commanding the actuator force $F_A$ acting on the equivalent mass. $F_A$ is in turn controlled using the feedback from the sensor on the fingertip, and a control law of the type {proportional + saturation + feedforward} (cf. e.g. [Salisbury,84b]). The responses of this system to impulse, ramp and sinusoidal inputs have been simulated. In fig.8–a,b are shown the responses of a system whose parameters correspond to a possible robotic hand, for an external sinusoidal disturbance and two values of the dependability figure $\alpha/\beta$.

The figure shows how a very conservative choice of $\alpha/\beta$ (fig. 8–b) can compensate also for dynamic effects related to physical implementation of the optimal trajectory of eq.5 (the optimal trajectory is also drawn in fig.8 for reference).

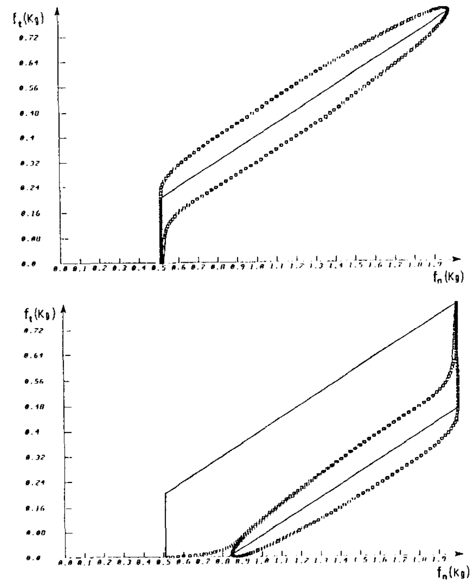


**FIG.8:** *Simulation results with sinusoidal disturbance for $\alpha/\beta = \infty$ (a) and $\alpha/\beta = 4$ (b)*

***Experimental Results.*** The method for grasp robustness augmentation described in section 2 has been experimentally evaluated at MIT-AI Lab using the following setup and procedures: a sensorized fingertip [Brock,85] has been mounted on the distal phalanx of the 'thumb' finger of the Salisbury hand [Salisbury 82]; the sensor employed the solution algorithm described in [Bicchi,89]. The fingertip surface consists of a hemisphere on top of a cylinder, and is realized with stainless steel. The very low compliance and friction characteristics of this material are unfavourable for grasp stability; high-firiction, compliant covers can be used to enhance those characteristics. The other two fingers of the hand, without IT sensing capabilities, had fingertip covers with much higher friction than the active one, and acted only passively to counteract the thumb forces and the external disturbances; disturbances were generated by gravity or by directly stimulating the grasped object to slip. In the initialization phase, data concerning the available object strength ($F_{crush}$) and the nominal value of contact force are input; the friction coefficient pertaining to the fingertip-object contact is measured using the procedure described in [Bicchi,89]. The hand grasps the object, pressing on it with the desired force; successively, the active finger increase the normal component of its contact force according to variations of friction ratio due to external stimuli.

The system proved to be able to discern, and promptly signal, istants when the friction limit was overcome; these corresponded well to real slip motions, as they could be detected by visual inspection. The sensor could as well perceive when the normal force required to balance disturbances was higher than $F_{crush}$. In both cases, this enabled the use of higher level strategies to deal such potentially dangerous conditions.

The implementation of normal force control on the active finger, carried out according to the standard {proportional + saturation + feedforward} scheme, sometimes resulted in limit cycles. Those problems, typical of force control *per se*, basically depend upon the stiffness of the mechanical system actuator-transmission-finger-object. However, tuning of the hand's stifness (which can be easily accomplished on hands designed according the "n+1 actuators for n joints" approach [Salisbury,82]) helped in most cases in realizing very effective adaptive grasps.

Fig.9-a,b gives experimental data (small squares) in the $f_n - f_t$ plane relating to the adaptive grasp of an object with medium fingertip-object compliance and friction characteristics (bare steel fingertip on a slick rubber hose) under random excitation forces, simulating unpredictable inertial and gravity loading on the object during manipulator movements, and external forces occurring e.g. in assembling tasks.

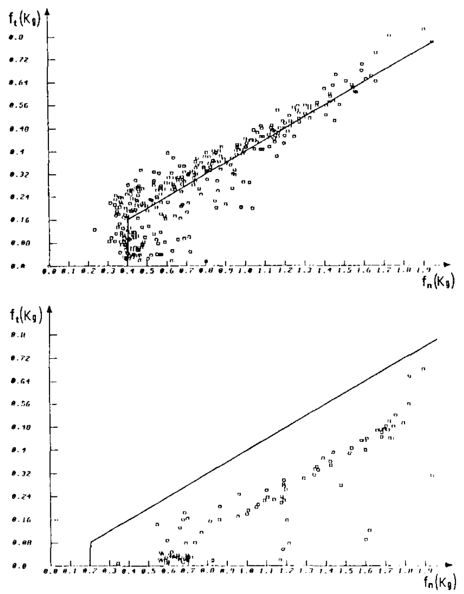

**FIG.9:** *Experimental results with randomly excited disturbances for $\alpha/\beta = \infty$ (a) and for $\alpha/\beta = 20$.*

In the experiment reported in fig.9-a the dependability figure, $\alpha/\beta$ , was set to infinity (i.e. total confidence in friction data). The diagram shows how the normal force control was not able to compensate for the high-frequency components of random excitation, generating scattered points about the optimal trajectory (however, it should be observed that not all these points corresponded to actual slippage, since the friction coefficient was purposely underestimated in the reported experiment). Control effectiveness limitations were due basically to long cycling times, entailed in turn by the non optimal, developmental computer architecture; in fact, while hand actuation algorithms ran on the three-level OOLAH system described in [Salisbury,85], sensor information and sensor-based control have been in this phase elaborated at the highest level, and four time-consuming message-passing operations were included in each cycle.

In the experiment described by fig.9-b $\alpha/\beta$ was set to 20. Also from these curves it is possible to argue how a conservative choice of $\alpha/\beta$ is mandatory to compensate for inaccuracies in the control of normal force. Finally, we observe that, although $\alpha/\beta$ has been selected so far almost empirically, it could be regarded as a function of statistical characteristics of friction measurements for the fingertip-object pair.

**CONCLUSIONS.** The aim of this paper has been to introduce a new approach to grasp force optimization and control, consisting in the use of real-time feedback from contact sensors in the hand's fingers. We referred in particular to "intrinsic" tactile sensors, which offer much richer information about contact stability than any other currently available sensor. Some simple strategies for optimizing grasp forces have been discussed, simulated and experimentally tested with good results. The generalization of these methods to exploit the potential capabilities of a fully sensorized dextrous hand is, in the authors' opinion, a promising and challenging task; such generalization has been only addressed in this paper.

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