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Integrated tactile sensing for gripper fingers

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ABSTRACT

This paper deals with the application of two different sensing technologies, namely force-torque sensing and tactile sensing, to the problem of controlling the grasp of robotic end effectors of the parallel-jaw type. The possible integration of force and tactile information is considered, aiming at the full exploitation of their sensing potentials. In particular, a method is proposed by which information about grasp stability, not obtainable from any of the two sensors alone, can be achieved.

INTRODUCTION

In order to perform increasingly sophisticated tasks a so-called "advanced" robot should possess the ability of controlling the interactions with its environment. This paper is concerned with a crucial aspect of the manipulator-environment system control problem, that is contact sensing.

By "contact sensing" we mean in general a collection of several information relating to the contact between a part of the robot arm (most often its end effector) and the surroundings: the intensity and direction of the forces and of the torques mutually transmitted through the contact points; the position of the contact points on the end effector surface; the stability of contact against possible slippage; the identification of local features such as the contact area shape, the surface texture and the presence of edges.

The principal sources of information on contact a present day robot can be equipped with, are force-torque sensors and tactile sensors.

Some different locations are possible for force-torque sensors: the robot environment (e.g. sensorized platforms), the arm, the wrist and the end-effector. Although any of these locations is, in principle, suitable for being instrumented and for providing the required force measurement, the tendency in modern manipulators is to bring the sensors as close as possible to the origin of their information, i.e. to the contact location, so that most friction and inertial disturbances can be eliminated. Some instrumented grippers incorporating force-torque sensors in each finger which allow the control of both external and internal (grip) forces, are now commercially available |1|.

Tactile sensing is concerned primarily with the local features of the contact, e.g. the location and geometry of contact area and the distribution of contact pressure. Most of present tactile sensors consist of an array of pressure sensitive elements (taxels) distributed over pads fixed to the end effector |2|.

Although essentially local, tactile sensing does not strictly require direct sensing on the surface where contact occurs. In fact, some of the characteristic features of tactile sensing can be also implemented by interpreting contact geometries from force measurements, as proposed by J.K. Salisbury |3|.

In this paper we present an integrated approach to automated tactile sensing, i.e. the integration in a simple end-effector (a parallel jaw gripper) of two sensing modalities such as force-based (or "intrinsic") and distributed ("skin-like") tactile sensing.

Advantages and shortcomings of each approach are discussed, along with a brief summary of the state of the art in both techniques.

The main effort of the paper shall be to demonstrate that the integration of the two sensing methods in the gripper fingers, far from being simply redundant, allows the full exploitation of sensing capabilities in a synergetic way.

A prototype gripper finger equipped with a novel 6-component force-torque sensor and a planar array of pressure sensitive elements based on the piezoelectric properties of polyvinylidene fluoride (PVDF) realized in our laboratory in order to experimentally assess integrated tactile sensing, will be described in the paper.

Finally, preliminary experimental results on tests of the proposed method are presented.

SKIN-LIKE TACTILE SENSING

The physical interaction between the robot end effector and the external environment can be detected by utilizing tactile sensors positioned over the surfaces of the end-effector where contact occurs. The way in which the properties of the physical contact are transduced in proper data for further analysis, i.e. for the control of the end effector during exploratory or grasping tasks, strictly depends on sensor technology. Most often the active surface of a tactile sensor consists of a set of several sensing elements arranged in a regular pattern, e.g. an orthogonal grid, and capable of measuring distributed contact forces |2|.

Other contact-related properties, such as material thermal conductivity, or also, in some cases, surface temperature, texture or moisture |4|, can be also detected by a tactile sensor.

Several technologies have been utilized in tactile sensing. Among the most used and promising, we can mention conductive rubber, piezoelectric, capacitive, magnetic and optical techniques |5|.

Consider the case of tactile sensors incorporated into the parallel jaws of a gripper: from a purely geometrical point of view, a binary image can suffice to recognize the position and orientation of the contact region with respect to a coordinate frame relative to each jaw. From the same binary image also local geometrical features of the contact area like sides, holes or vertices, can be extracted.

Grey level tactile images contain additional important information, such as the local distribution of the forces acting on each sensing element of the tactile sensor. At present, while a number of devices can measure the normal component of the forces acting on the active sites of the sensor, not many sensors exist which are capable of detecting locally shear and torque, as would be extremely important not only for exploratory but also for grasping operations (where the determination of shear forces could control and avoid the slippage of the grasped object). Different approaches to this problem have been presented in |6| and |7|.

Limited spatial resolution, low force sensitivity and hysteresis are frequent limitation of present tactile sensor. New design and technologies can improve to some extent some of these drawbacks, but not eliminate the intrinsic limitation in reconstructing the integral values of contact forces and torques, which derives from the finite resolution of an array tactile sensor.

In the following, a method is proposed for overcoming the limitations of a low spatial resolution tactile sensor, capable of measuring only the normal component of distributed contact forces, by integrating it with a resultant force/torque sensor.

FORCE SENSING FOR CONTACT ANALYSIS

As mentioned before. a contact geometry analysis technique based on indirect force measurements was proposed by J.K. Salisbury in 1984 |3|. The basic idea is that a multi-component force sensor is able to provide enough information to compute some of the most significant parameters involved in the contact, provided that the sensor is solidal with one of the contacting surfaces and that a geometrical description of the sensor-surface system is available. For brevity's sake, we call a sensor based on this principle an "intrinsic" tactile sensor, referring to the fact that a model of inherent features of the sensor is needed. In fact, for simple surface geometries and under some realistic hypotheses on contact conditions, the basic information required from a "contact sensing" device (as listed in the introduction) can be obtained, except for the local contact features, by means of very simple geometrical and force-balance relations. Some applications of this method have been already proposed for instrumenting the fingertips of robotic "dexterous" hands, using spherical tip surfaces |8| |9|.

The main issue in the design of such sensors is to realize a multicomponent force sensor which is not only precise, robust and easy to process but also small and lightweight as required for being located in the end effector as close as possible to the contact zone. Although almost all kinds of transducing methods proposed for conventional force sensing (capacitive |10|, electrooptical |11|, etc.) are in principle suitable for these devices as well, probably the well established strain gauge technique is still the most reliable, precise and cheap one.

With respect to a skin-like tactile sensor, an intrinsic tactile sensor has several advantages: the first is that the measure of resultant contact force and torque is direct, allowing fine control of manipulative tasks. Furthermore the tangential components of contact forces originated by the friction between the fingerpad and the object can be distinguished by force sensing, and this information can be used in order to prevent or control slippage |9|. Finally, owing to the low number of sensing elements of a force sensor compared to the number of sensing elements in a high-resolution tactile sensor, information on contact can be provided by a force sensing based contact sensor at much higher rate.

On the other hand, intrinsic tactile sensing cannot provide information on local contact features, such as the extension and shape of the contact area: in the case of planar finger pads, which is studied in this paper, this is indeed an important drawback, since most contacts occur on a large area of the pad.

INTEGRATION OF FORCE AND TACTILE SENSING

Consider first the information on the contact that we can obtain using force sensing associated with a planar surface (for instance the jaw of a gripper). Referring to Fig. 1, let the coordinate system O-XYZ be the force sensor reference frame, i.e. the axes along which the rectangular components of the resultant force and torque originated by the contact are measured: the vectors $\underline{F}$ and $\underline{M}$ in Fig. 1 represent, respectively, those force and torque. Assume that the pad surface lies in the Z=0 plane: this can be done without any loss of generality, because the knowledge of $\underline{F}$ and $\underline{M}$ in a reference frame guarantees the knowledge of the resultant force and torque in any other frame. Contact will occur at points of the pad plane whose ensemble is defined as the contact area "A".

We make the additional assumptions that only pure forces (no torques) can be exerted through each contact point, and that the forces exerted on the fingerpad have negative component along the Z axis (that is, we exclude adhesive actions between the end effector and the grasped objects). Finally, we adopt for friction the classical assumption of dry contact, i.e. the friction-to-normal force ratio is lower than (or equal to) a static friction coefficient Cs, at rest, and it equals a constant value (dynamic friction coefficient, Cd) when a relative motion of the parts occurs. In the latter case, the direction of friction force is such as to oppose to the velocity in that point.

In these hypotheses, it can be shown that one unique point exists, respect to which the system of contact forces is equivalent to a pure force $\underline{f}$, plus a moment $\underline{m}$ perpendicular to the pad plane. This point, that will be referred to as the contact centroid C, lies always within a convex closed curve that bounds the contact area A |3|.

Using the force sensor information $\underline{F}$, $\underline{M}$, we can then characterize the contact by means of the relations:

$$\underline{C} = \frac{1}{Fz} (-My, Mx, 0) \qquad (1)$$

$$\underline{f} = \underline{F} \qquad (2)$$

$$\underline{m} = (0,0,Mz+\frac{MyFy}{Fz}+\frac{MxFy}{Fz}) \tag{3}$$

Using two such sensors on the jaws of a gripper, it is then possible to control both the internal (grip) forces exerted upon a grasped object, and the external forces that occur, for instance, in assembly tasks. Furthermore, the position of the contact centroid C represents a useful, although partial, information on the location of contact area.

As for the problem of the stability of contact condition, we derive another important information from force sensing. Consider the situation depicted in Fig. 2a. In this case, the body pressed between the sensorized jaws with a normal force f_z is also subject to tangential actions that tend to translate it. Instability due to slippage will not occur until the ratio between the intensity of tangential and normal forces is lower than the static friction coefficient Cs. This is illustrated by the following relation:

$$R = \frac{\sqrt{Fx^2+Fy^2}}{Fz} \leqslant Cs \tag{4}$$

Of course, Cs has a different value for each material pair, and varies in a broad range as the contact conditions (temperature, lubrication) vary; however, a safe estimate of Cs will enable the use of eq. (4) in an adaptive grasping strategy, suitable for the manipulation of fragile and/or slippery objects.

In case the above slippage prevention strategy fails, the body can move in the grip, and a possibly dangerous loss of control may arise. However, the sudden decrease of R, from the value of Cs to the value of the dynamic friction coefficient Cd, can be readily felt by the force sensor, and the detected slippage may be stopped, for instance, by increasing gripping force.

Consider now the case of a body pressed onto the jaw surface, and subject to tangential forces or torques which tend to rotate it about an axis normal to the jaw plane, as depicted in Fig. 2b. In this case, nothing can be said about possible slip motion, because the moment that can be resisted by frictional forces depends not only on the normal force, but also on the shape of the contact area.

Finally, with a force sensor alone, we cannot say anything either about possible instabilities of the grip in respect of rotations about axes parallel to the jaw plane, as in the case illustrated in Fig. 2c.

Augmenting a force-sensorized gripper jaw with a tactile sensor of the skin-like type, enhances its sensing capabilities in two ways.

Firstly, a distributed tactile sensor will obviously add all its peculiar information, allowing the gripper to sense also the local features of the grasped object that can be useful in order to recognize the object's position, orientation, or even identity.

Secondly, the information contained in an image of the contact area can be integrated with that provided by the force sensor in order to address the unsolved contact instability problems outlined above.

Consider first the case of incipient rotational slippage (Fig. 2b) when a matrix tactile sensor is placed on the pad surface. In Fig. 3 a low resolution tactile sensor is shown for simplicity, having larger dots where the sensitive elements of the matrix are pressed by the base of the grasped object. In general, frictional forces between the base and the pad are required to resist a shear force $\underline{f}_T$ and a torque m, whose values are supposed to be measured by the force sensor of the jaw.

If the actual contact area is approximated by the inner excited taxels alone, as is reasonable for high resolution sensors, we can suppose that each taxel contributes to equilibrate the normal force f_z proportionally with the pressure it measures.

Alternatively, if a grey-scale tactile sensor is not employed and only binary (touch-non touch) information is available, we can further hypothesize a linear distribution of the normal pressure over the taxels, such that the normal force f_z applied at the centroid C is equilibrated.

After that the normal force exerted on the excited taxels is estimated, also the maximum tangential force each of them can resist is known in modulus (provided that also the value of the static friction coefficient is estimated). This modulus is represented in Fig. 3 by the radius of the corresponding friction circle drawn around each active taxel.

In the critical condition, just before slippage occurs, the vectors representing friction forces will have their origin in the center of the taxel, the end point on the circle around it and direction normal to the line connecting the taxel with the velocity pole P_v of the immediately subsequent act of motion.

In order to calculate the maximum value of the torque m that can be safely resisted by friction, we must then find this velocity pole: if eq. (4) is verified, than P_v exists in the plane of the jaw at a finite distance from the origin.

Let (Xp,Yp) be the pole coordinates and (Xi,Yi) be the i-th taxel coordinates in the jaw reference frame (see also Fig. 1); then we can write the force balance equation along the X and Y axes:

$$
\begin{aligned}
f_x &= \sum_{i=1}^{n} \frac{-Cs\cdot Fi\cdot(Yi-Yp)}{[(Xi-Xp)^2+(Yi-Yp)^2]^{1/2}} \\
f_y &= \sum_{i=1}^{n} \frac{Cs\cdot Fi\cdot(Xi-Xp)}{[(Xi-Xp)^2+(Yi-Yp)^2]^{1/2}}
\end{aligned}
\qquad (5)
$$

where f_x, f_y are the tangential components of the measured global force $\underline{f}$ (see eq. (2), and Fi's are the normal force values on each of the n active taxels. Solving this nonlinear two-equation system for the unknowns Xp,Yp, we can then verify the inequality:

$$
R' = \frac{m}{\sum_{i=1}^{n} [(Xi-Xp)^2+(Yi-Yp)^2]^{1/2} Fi} \leqslant Cs \qquad (6)
$$

which is the analogous of eq. (4) with respect to rotational slippage.

Eq. (5) fails if P_v coincides with the position of a taxel, a case that is likely to occur only if very few active taxels are present. Each taxel should be evaluated as a possible velocity pole, supposing that the tangential forces F_{Px}, F_{Py} contributed by the j-th candidate taxel are unknown, and verifying that the balance equations:

$$
\begin{aligned}
f_x &= F_{Px} - \sum_{i\neq j}^{n} \frac{Cs\cdot Fi\cdot(Yi-Yp)}{[(Xi-Xp)^2+(Yi-Yp)^2]^{1/2}} \\
f_y &= F_{Py} + \sum_{i\neq j}^{n} \frac{Cs\cdot Fi\cdot(Xi-Xp)}{[(Xi-Xp)^2+(Yi-Yp)^2]^{1/2}}
\end{aligned}
\qquad (7)
$$

are satisfied with $\sqrt{F_{Px}^2 + F_{Py}^2} \leqslant Cs\cdot Fj$: this corresponds to assume that the candidate taxel acts as a perfect hinge. If the j-th taxel is the P_v, we can use eq. (6) to assess contact stability by simply omitting the j-th term in the sum.

Finally, the integration of force and tactile sensing in the jaws of the end effector can provide useful information also in the instability case of Fig. 2c. In fact, an estimate of the robustness of the grip can be obtained by observing the position of the centroid C with respect to the smallest convex closed curve bounding the active taxels, since obviously the grip becomes unstable when the resultant of the normal forces passes outside the base of the object.

EXPERIMENTAL

In order to assess experimentally the feasibility and the results of the integrated tactile sensing approach outilined above, we utilized the parallel-jaw gripper sketched in Fig. 4. While the actuation mechanism, the bearings and the carriage guides are those of a commercial gripper, a new pair of jaws incorporating force and tactile sensors was purposely designed.

The force sensor is a strain gauge instrumented beam which connects the gripper carriage with the finger pad. The beam, machined from aluminum alloy, has a thin ring cross-section; six strain gauges measure its deformation under applied loads. The design of this force sensor is the result of a computer-aided optimization procedure, whose details have been discussed in |9|.

The tactile sensor, directly supported by the planar jaw surface, is based on the technology of the piezo-pyroelectric polymer PVDF.

The structure of the sensor, already described in a previous paper |12|, comprises a rigid printed circuit board (PCB) supporting a 110 micron thick PVDF film. On the upper side of the PCB, the pattern of the sensing elements is obtained by arranging 128 circular electrodes, having a 1.5 mm diameter and 3.2 centre-to-center spacing, according to an orthogonal grid. The principle of operation is based on the generation of electric charge by piezoelectric effect in the thickness of the PVDF film when pressure is applied. The charges are collected by each electrode, multiplexed, amplified, and processed in order to reconstruct the force signal waveform. The preprocessing technique has been described in detail in |12|, where data on sensor force sensitivity and bandwidth were also provided.

A semi-integrated miniaturized version of this tactile sensor has been developed and is presently manufactured by Polysens S.p.A. |13|.

Thus far, experimental tests have been carried out on a simplified testbed, comprising only one sensorized finger on which various objects were placed and pressed in a controlled manner. All the software necessary to manage the force and tactile sensors, and the integration of their information, run on a DEC computer (uPDP11/73).

We present here an experiment performed by indenting the gripper pad with the base of a cylindrical object. The procedure to obtain the information from the integrated sensory system can be illustrated with reference to Fig. 5, in which the computer graphic display, shows the tactile sensor grid on the right (each taxel having its center on the crossing of two lines).

The program evaluates at first the information of the force sensor: by exploiting relations (1),(2),(3), the normal and tangential components of contact force, and the torque acting in the jaw plane, can be displayed (see Fig. 5a,b) along with the position of the contact centroid over the jaw pad (point CC in Fig. 5c).

Using a safe estimate of the static friction coefficient pertaining to the simulated contact conditions, eq. (4) is then utilized in order to warn about possible translational slippage.

The tactile sensor is then scanned; in Fig. 5c the pressed elements are indicated with a small dot and the actual shape of the contact surface is superposed to the display for reference.

Based on the position of the contact centroid relative to the active taxels, a distribution of contact pressures over the active elements of the tactile sensor can be derived even if the signal is thresholded and a binary image is obtained. It should be noted that such an evaluation of normal pressure distribution assumes that contact occurs only on the taxel centers, and that the low resolution of the tactile grid can badly affect the result. However, since a grey-level information is provided by the tactile sensor of our gripper, the integral measure of normal force has been utilized to estimate local pressure by taking into account the relative contribution of each active taxel. This method is likely to provide a better approximation of the real pressure distribution than in the case of a binary image.

Finally, the program evaluates the danger of rotational slippage, using the same estimate of the friction coefficient; the maximum shear force that can be exerted on each taxel is represented in Fig. 5-c, with the same type of convention as in Fig. 3. Each taxel is sequentially tested as a velocity pole candidate using eq. (7). If no result is obtained, a rotation about the contact centroid is hypothesized: if eq. (5) is not satisfied, an iterative procedure is initiated using the centroid as the first guess. Although any classical algorithm is suitable for the iterative solution of the two non-linear equations system (5), we found that an ad hoc algorithm converges very rapidly in most cases. The algorithm, which tends to exploit the peculiar nature of the system relationship, sets the search direction normal to the vector of residues of eq. (5), and adjusts the search step according with the variations of the modulus of the residues.

When a point is found which satisfies (within some tolerance bounds) eq. (5), the program displays it (see point P_v in Fig. 5-c) and calculates the maximum torque that can be resisted by frictional forces by applying eq.(6). This value is compared with the torque measured by the force sensor, and warning messages are sent if necessary.

Quantitative values referring to the above experiment are reported in Fig. 5; in this case, the contact was fairly stable, with regard to both traslational and rotational slippages.

CONCLUSIONS

The purpose of this paper was to verify the intuition that integrating force and tactile sensing may facilitate the control of robot manipulation. This hypothesis has been discussed referring to the specific case of a robot gripper incorporating a piezoelectric polymer tactile sensing array and a strain gauge-based multicomponent force/torque sensor, both designed and fabricated in our laboratory. It has been demonstrated, for the case of slippage avoidance, that the integration of force and tactile data provides information not obtainable by each individual sensing modality.

Although the results presented in this paper are only preliminary, they are encouraging enough to justify further research efforts on various theoretical and experimental aspects of sensorized gripper-based manipulation.

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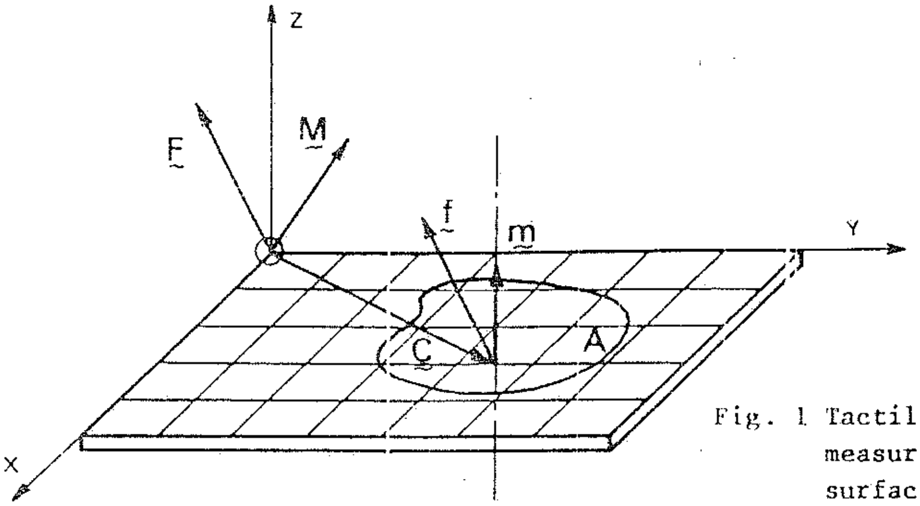


Fig. 1 Tactile information from force-measurement applied to the planar surface of a gripper jaw.

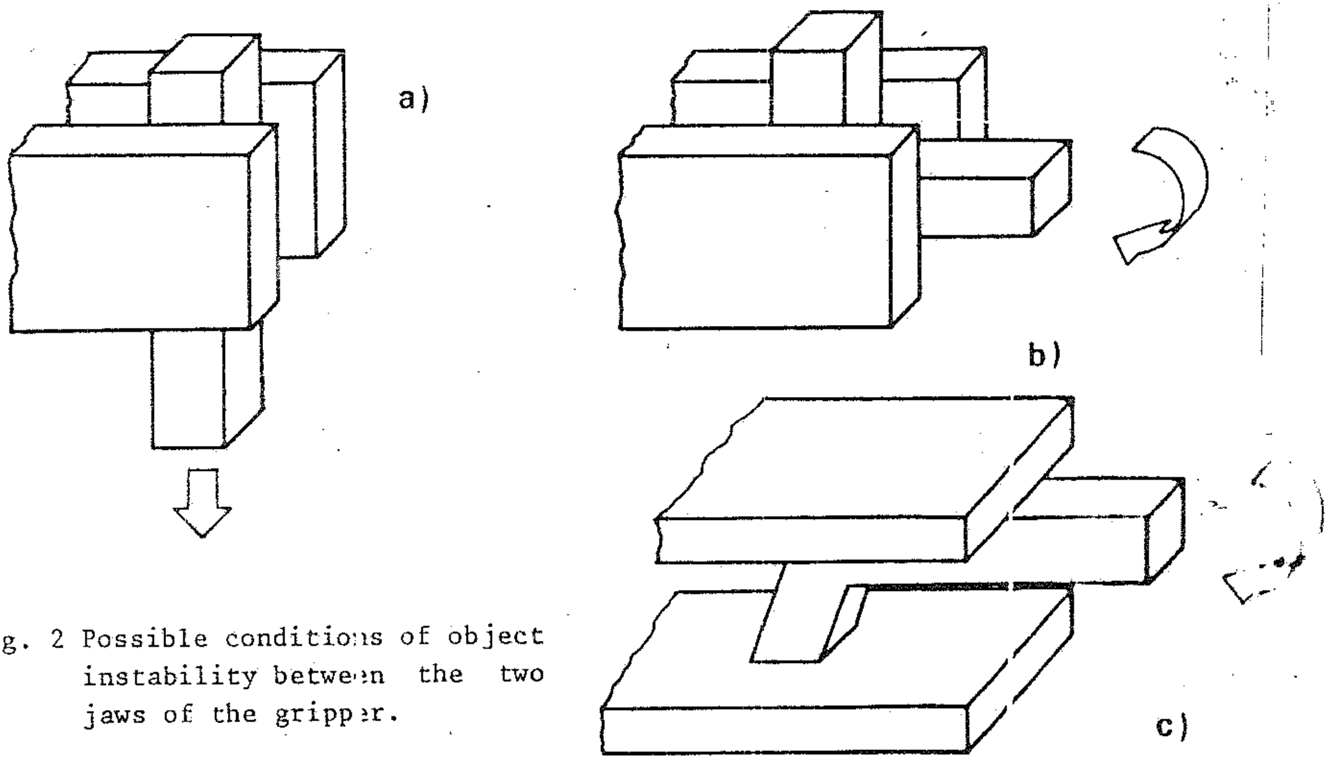


Fig. 2 Possible conditions of object instability between the two jaws of the gripper.

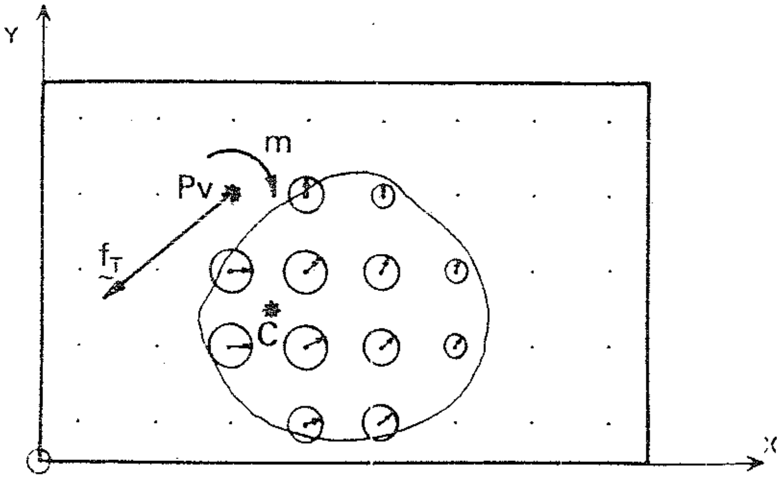


Fig. 3 A scheme representing the hypothesized distribution of local tangential forces on the points of the tactile image. Pv represents the velocity pole and C the centroid.

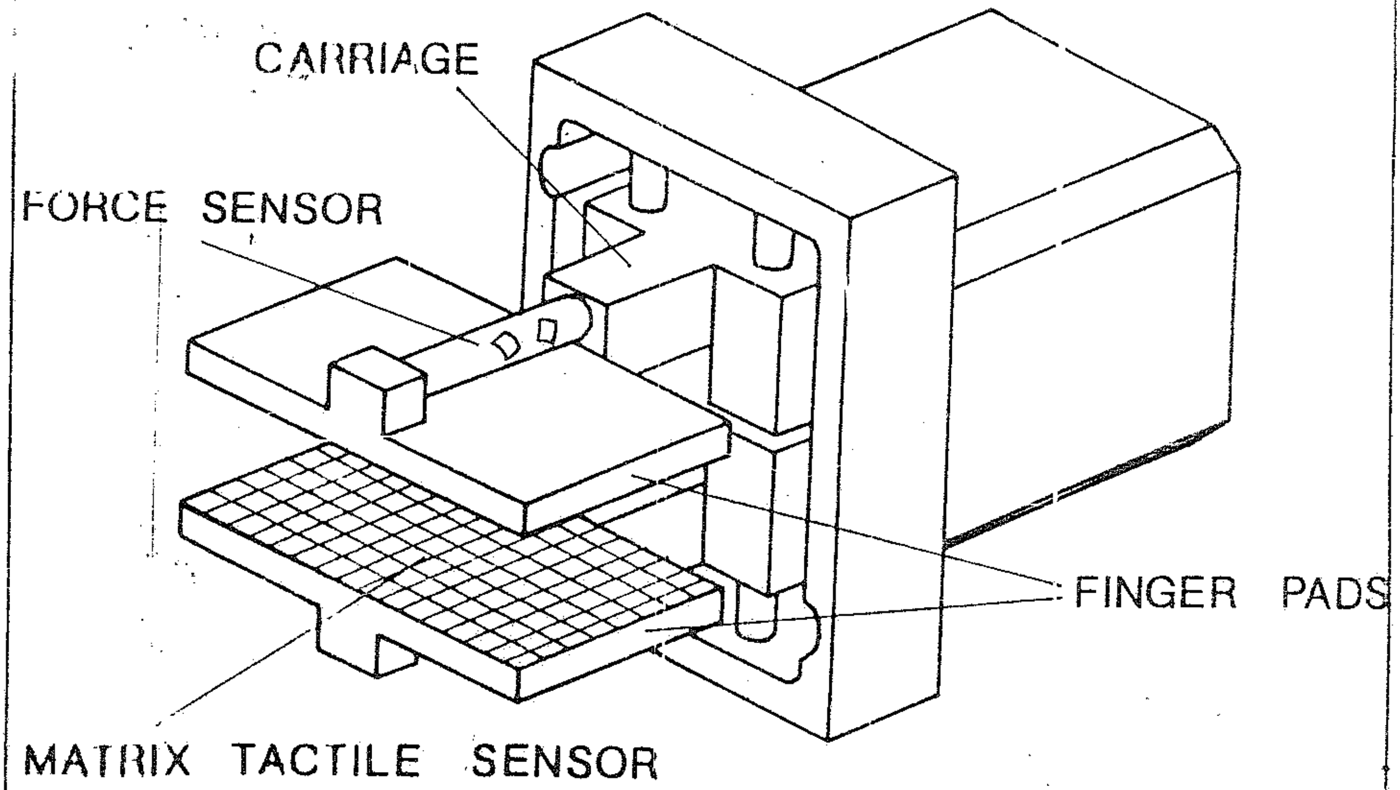
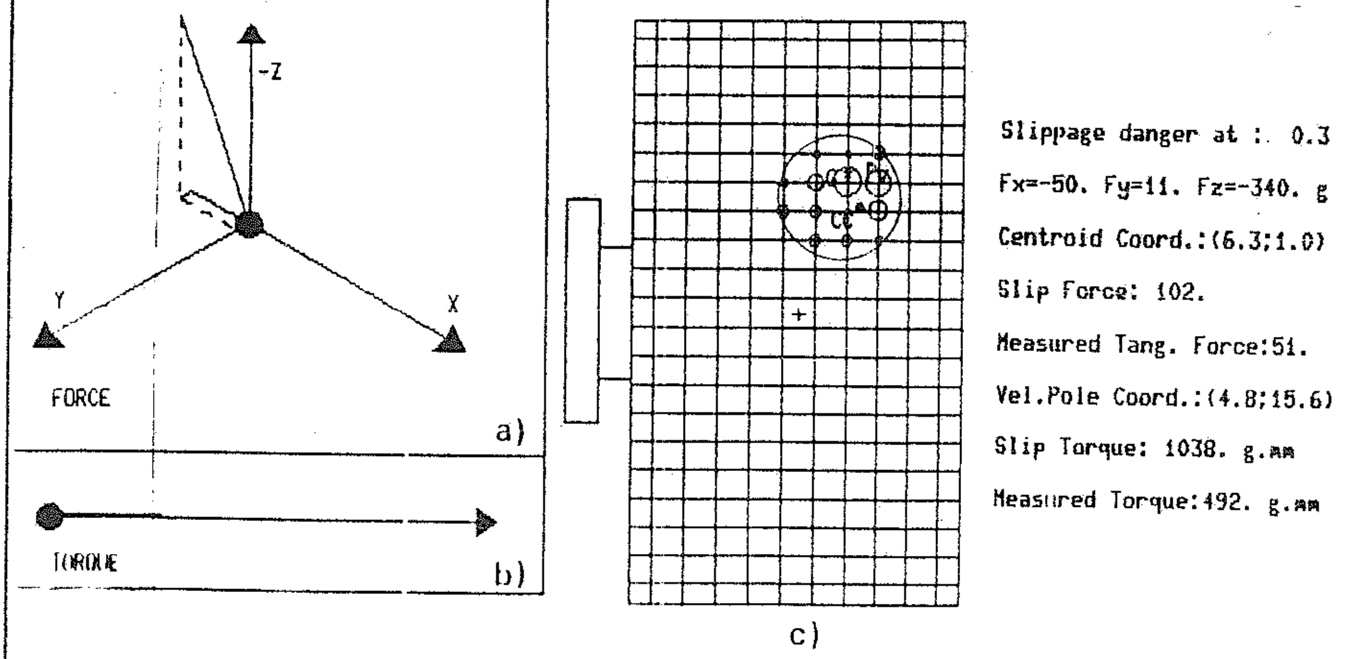


Fig. 4 The parallel-jaw gripper used in our experiments: the tactile and force sensors are shown.



```
Slippage danger at : 0.3
Fx=-50. Fy=11. Fz=-340. g
Centroid Coord.:(6.3;1.0)
Slip Force: 102.
Measured Tang. Force:51.
Vel.Pole Coord.:(4.8;15.6)
Slip Torque: 1038. g.mm
Measured Torque:492. g.mm
```

Fig. 5 The experimental results illustrating the information on force a) and torque b) obtained by the force sensor, and the tactile image c) where the radius of circles on each activated tactel represents the value of maximum local tangential force.