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MULTIPLE SENSING FOR DEXTEROUS END EFFECTORS

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ABSTRACT

In this paper the problem of investigating the sensory aspects of dexterous manipulation and active touch is approached by designing a simple robot system comprising one articulated finger. The system can be viewed as a testbed for replicating some sensory-motor procedures typical of human tactile sensing. The characteristics of each component of the robot system (finger, sensors and control architecture) derived from a system analysis of the functions required for robotic fine manipulation and haptic perception. In particular, the different roles of fingertip force/torque sensors, proximity sensors and of tactile sensors are pointed out.

Based on the indications of some preliminary experiments carried out on the robot finger system equipped with a ferroelectric polymer-based skin-like tactile sensor, a new multiple sensing fingertip has been designed, intended for eventually incorporating most of the sensory functions required to perform the sophisticated exploratory tasks typical of haptic perception. In this paper a fingertip sensor possessing only a few basic sensing capabilities is described.

Finally, an example of integration of sensor information providing an effective and unique means to prevent incipient slippage is discussed referring to a robot gripper equipped with a resultant force/torque sensor and with distributed tactile sensors. This example demonstrates that multiple sensing can be "fused" in a synergetic way, rather than being simply redundant.

1. INTRODUCTION

Most of the tasks that could be executed by a dexterous robotic hand can be classified as either manipulative or exploratory. Although the ideal characteristics of devices designed purposely either for manipulation or for tactile exploration may differ to some extent, both applications share some basic requirements. Among these common requirements, the ability to control efficiently the forces that the hand exerts on the environment has a system analysis of the functions required for robot fine manipulation and haptic perception."

Based on the indications of experiments carried out on the robot finger system, wich was equipped with a ferroelectric polymer-based, skin-like tactile sensor, we have designed a new multiple sensing fingertip intended to eventually incorporate most of the sensory functions that we believe are required in order to perform the very sophisticated exploratory tasks typical of haptic perception. In this paper we describe a preliminary configuration of the fingertip sensor, which possesses only some fundamental sensing capabilities. At present, in fact, the fingertip sensor includes a strain gauge-based force and contact resolving sensor, an optical tactile sensor, and a piezoelectric polymer ultrasonic range sensor.

The implications of the use of this redundant sensor in some different exploratory procedures are discussed.

2. THE MULTIPLE SENSING FINGERTIP

The fingertip sensor has the configuration depicted in Fig. 1 (29).

The fingertip incorporates in the base a force and contact sensor. The cover contains an array of tactile sensors capable of detecting locally the normal and the tangential components of contact forces, as well as an array of curved polymer transducers, which have the primary function of emitting and receiving US waves for range sensing, but also the possible function of a very sensitive tactile receptor for sensing vibration patterns (4).

2.1. FORCE AND CONTACT RESOLVING SENSOR

A force sensor is a device which measures, in a particular coordinate frame, the six components of the "generalized force" vector (i.e. three pure forces and three torques) that is exerted through the sensor itself. This task is usually carried out by measuring the deformations that the applied load causes in a suitable mechanical part of the sensor.

An extensive literature is available on robotic force sensors (5)(6)(7). In most cases, however, force sensors have been designed to fit the wrist of a robot arm: thus, specifications concerning size, weight, robustness, etc., differ considerably from those required for a fingertip force sensor.

A fingertip force sensor based on a modification of the original Scheinman design (6) has been recently developed to be incorporated in the finger of the Stanford/JPL hand (8). Although this sensor proved to be rather efficient, a simpler structure may be desirable in order to integrate the force sensor with other sensing systems in the same fingertip.

By investigating the theoretical feasibility of a force sensor using only 6 strain-gauges bonded to a general shape mechanical support, we devised an extremely simple, miniaturized sensor configuration, in which the can be illustrated referring to Fig. 3.

The light provided by a constant intensity optical source is guided into a transparent plate (that can be shaped as the fingertip) by total internal reflection at the air-plate interface. If a rubber element located at the top surface of the transparent plate is pressed on the same plate by the external load, the rubber-plate contact surface varies and this influences the local light reflection conditions. In that area, in fact, the light can diffuse out of the plate. The amount of diffused light depends on the dimensions of the contact area between the rubber and the plate and, hence, on the local indentation of the rubber pad. The intensity distribution of diffused light can be interpreted as a "tactile image".

Some investigators have recently exploited this principle for the development of array sensors able to provide tactile images produced by the contact between an object and a rubber sheet incorporating a distribution of pyramidal, conical or hemispherical asperities (12)(13)(14). Very recently, Begej has also implemented a sensorized fingertip which has hemispherical shape and incorporates 256 tactile elements, based on the above optical principle (15).

In practice, the tactile images generated by all these devices are associated with the distribution of normal forces acting on the sensor surface. A method which extends the frustrated light principle to the measurement of tangential contact forces has been recently proposed by King and White (16), in a device in which tangential forces are correlated with the position of mobile elements consisting of small, elastically connected, rubber spheres.

By improving on previous examples of tactile sensing devices based on the total internal light reflection technique, we have designed a fingertip-shaped tactile sensor which incorporates an array of microlevers capable of detecting normal and tangential actions. As shown in Fig. 1, the tactile sensing elements would be disposed non-homogeneously over the fingertip surface, according to a foveal concept (17), which attributes most sophisticated sensing functions, both in terms of spatial resolution and of different sensed variables (proximity, temperature, chemicals), to a small area of the fingertip surface ("fovea"). A description of the prototype microlever sensor we have designed is given in a following paragraph.

2.3. US RANGE TRANSDUCER

As already pointed out, range sensing can be very important for a robot end-effector because it allows not only to detect the presence of objects, but even to reconstruct 3-D images of the external environment (18). Compared with other range sensing techniques, US have a number of attractive features (19). As preliminarily investigated by Shoenberg (20), and by Schoenwald and Martin (21), it is possible to use polyvinylidene fluoride (PVF2) curved transducers to emit and receive US waves. We have elaborated this concept by designing an array of curved, alternatively concave and convex, PVF2 transducers. Each concave element emits a focused thickness. A bending load of 10 N applied at the tip of the cylinder produces a tip deflection of 0.4 mm and a strain of 1.8x10 at its fixed end. Larger accidental loads would cause the thin pipe to lean against a thicker cylinder, which acts as an overload protection (see Fig. 2).

The strains induced by external forces in the cylinder are measured in this prototype version by 6 foil strain gauges, whose signals are conditioned and amplified by a purposely designed electronic unit. Then, signals are converted in digital form and sent to a computer for further processing.

The following calibration matrix, showing the normalized sensor sensitivities to the six components of the applied load, has been obtained experimentally:

$$X = \begin{vmatrix} 1.02 & -0.01 & 0.00 & -0.01 & 0.01 & 0.01 \\ 0.01 & 1.01 & -0.03 & -0.01 & 0.00 & 0.00 \\ 0.01 & 0.01 & 0.99 & 0.05 & 0.00 & 0.01 \\ 0.01 & -0.02 & 0.00 & 0.98 & -0.01 & -0.02 \\ 0.00 & -0.01 & -0.02 & -0.03 & 1.02 & -0.02 \\ -0.01 & -0.01 & -0.01 & 0.04 & 0.04 & 0.99 \end{vmatrix}$$

Although this results is slightly worse than the crosstalk matrix of force/torque sensor designed with easier constraints, this sensor demonstrated the feasibility of the proposed methods.

3.2. OPTICAL TACTILE SENSOR

At present, we have fabricated and preliminarily tested an optical tactile sensor incorporating only one microlever element.

The microlever is rigidly connected to a base, on the bottom of which three highly compliant conical rubber elements are located. The contact force acting on the microlever compresses the three conical rubber elements against the plate. The optical signal produced by the light diffusing at the bottom of each rubber cone is collected by an optical fiber and carried to a photodetector.

Assuming that: a) no pulling forces and no torq ues are exerted on the microlever tip; b) lateral displacements of the base are prevented by suitable constraints, and c) the microlever is not higher than a value, h, resulting from equilibrium considerations, the amount of light detected at the output of each optical fiber can be associated with the normal reactions R ,R and R at the points corresponding to the three rubber cones, as indicated in Fig. 5.

Referring to the scheme reported in the same Fig. 6, in which the constraints that prevent lateral displacements of the base are indicated with R and R , and the components of the contact force exerted on the microlever tip are Fx, Fy, Fz, it is possible to write the following different resonant frequency, were obtained on the same plexiglass frame. Resonant frequencies were 65, 105, 131, 174 and 262 KHz, respectively. We have tested the directivity of each transmitter, using the experimental setup sketched in Fig.8

In order to map the US beam accurately, and without altering it significantly, we used an ad hoc designed, miniature, PVF2 receiver, having a diameter of 1 mm.

The focusing effect of the concave shape has been assessed for all the five emitters. In Fig. 9 a,b, a particular case is presented, in which the US beam emitted by a concave transducer with ls=8mm, r=4.25 mm, fr=65 KHz is compared with that emitted by a convex emitter having the same dimensions.

4. EXAMPLE OF INTEGRATION OF FORCE AND TACTILE SENSING IN A ROBOT GRIPPER

As an example of integration of sensor information that can be regarded as redundant in some situations, but as functionally useful in other, the case of object manipulation carried out by a robot gripper equipped with a resultant force/torque sensor and distributed tactile sensors is discussed (28).

4.1. GENERAL CONSIDERATIONS

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. 10, 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. 10 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 parallel to the jaw plane, as in the case illustrated in Fig. 11c.

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. 11b) when a matrix tactile sensor is placed on the pad surface. In Fig. 12 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 $\underline{m}$, 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. 12 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 $\underline{m}$ 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:

$$f_x = \sum_{i=1}^{n} \frac{-Cs\ Fi\ (Yi-Yp)}{[(Xi-Xp)^2+(Yi-Yp)^2]^{1/2}}$$

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

based on the technology of the piezo-pyroelectric polymer PVF2.

The structure of the sensor, already described in a previous paper (26), 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 (26), 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. (27).

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 (μPDP11/73).

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. 14, 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. 14a,b) along with the position of the contact centroid over the jaw pad (point CC in Fig. 14c).

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. 14c 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

ACKNOWLEDGMENTS

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REFERENCES

1. J.K. Salisbury, "Kinematic and force analysis of articulated hands," Ph.D.Dissertation, Mechanical Engineering Department, Stanford University, May 1982.
2. W.D. Hillis, "Active touch sensing," MIT AI Memo AIM-629, Cambridge, MA, 1981.
3. R.S. Fearing and J.M. Hollerbach, "Basic solid mechanics for tactile sensing". Proc. 1st IEEE Int. Conf. on Robotics, Atlanta, pp. 266-273, 1984.
4. P. Dario, D. De Rossi, C. Domenici and R. Francesconi, "Ferroelectric polymer tactile sensors with anthropomorphic features". Proc. 1st IEEE Int. Conf. on Robotics, Atlanta, pp. 332-340, 1984.
5. B. Shimano, "The kinematic design and force control of computer-controlled manipulators". Ph. D. Thesis, Stanford University, 1978.
6. A.K. Bejczy, "Smart hand: Manipulator control through sensory feedback", Jet Propulsion Laboratory, Memo D-107, 1983.
7. C. Wu, "Compliance control of a robot manipulators based on joint torque servo", Int. J. Robotics Res., Vol. 4, n. 3, pp. 55-71, 1985.
8. D. Brock, S. Chiu, "Environment perception of an articulated robot hand using contact sensors", Proc. of ASME Winter Annual Meeting, Miami, 1985.
9. J.K. Salisbury, "Interpretation of contact geometries from force measurements". In: Robotics Research, M. Brady and R. Paul Eds., Cambridge, MA:MIT Press, pp. 565-577, 1984.
10. M.R. Cutkosky, J.M. Jourdain, P.K. Wright, "Skin materials for robotic fingers", Proc. 1987 IEEE Conf. on Robotics and Automation, Raleigh, pp. 1649-1654, 1987.
11. R.S. Fearing, "Touch processing for determining a stable grasp". Master's Thesis, Department of Electrical Engineering and Computer Science, MIT, Cambridge, MA, 1983.
12. K. Tanie, K. Komoriya, M. Kaneko, S. Tachi and A. Fujikawa, "A high resolution tactile sensor", Proc. RoViSeC 4, pp. 251-260, London, UK, 1984.
13. D.H. Mott, M.H. Lee, H.R. Nicholls, "An experimental very high resolution tactile sensor array". Proc. RoViSec, pp. 241-250, London, UK, 1984.

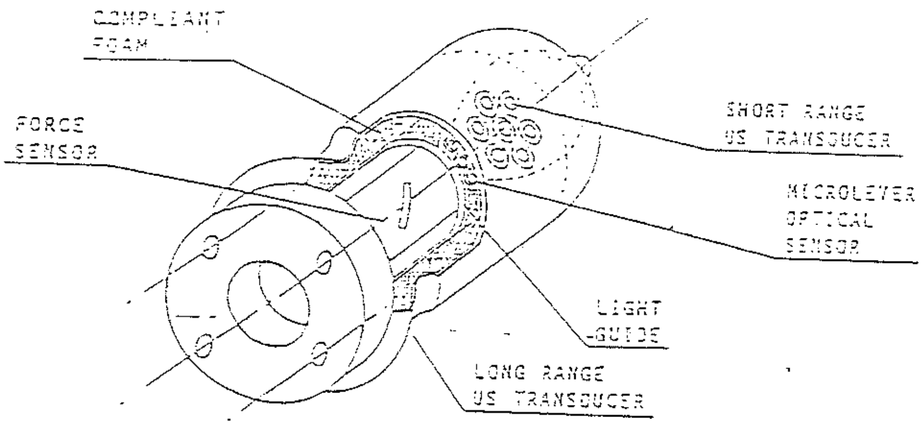


Figure 1. The multiple sensing fingertip

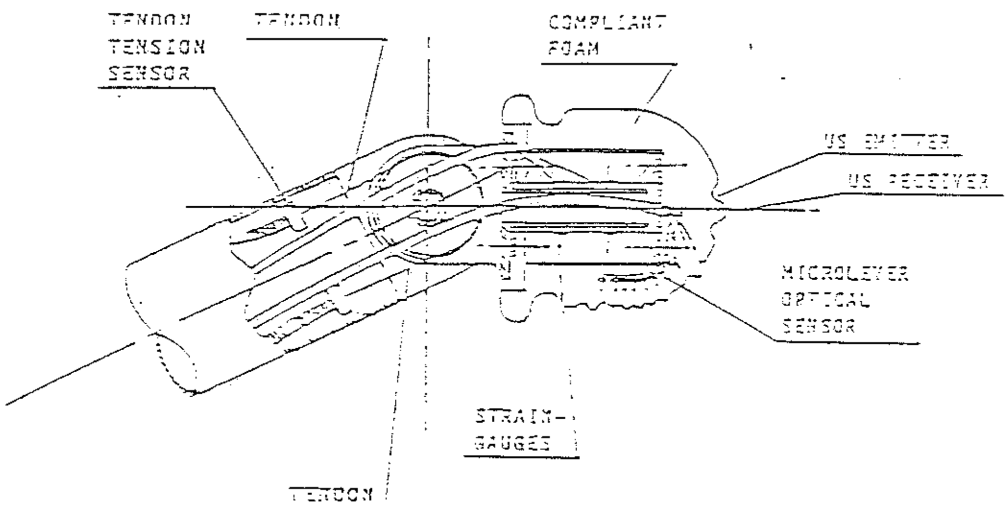


Figure 2. A cross section of the fingertip showing the strain gauge-based force and contact resolving sensor.

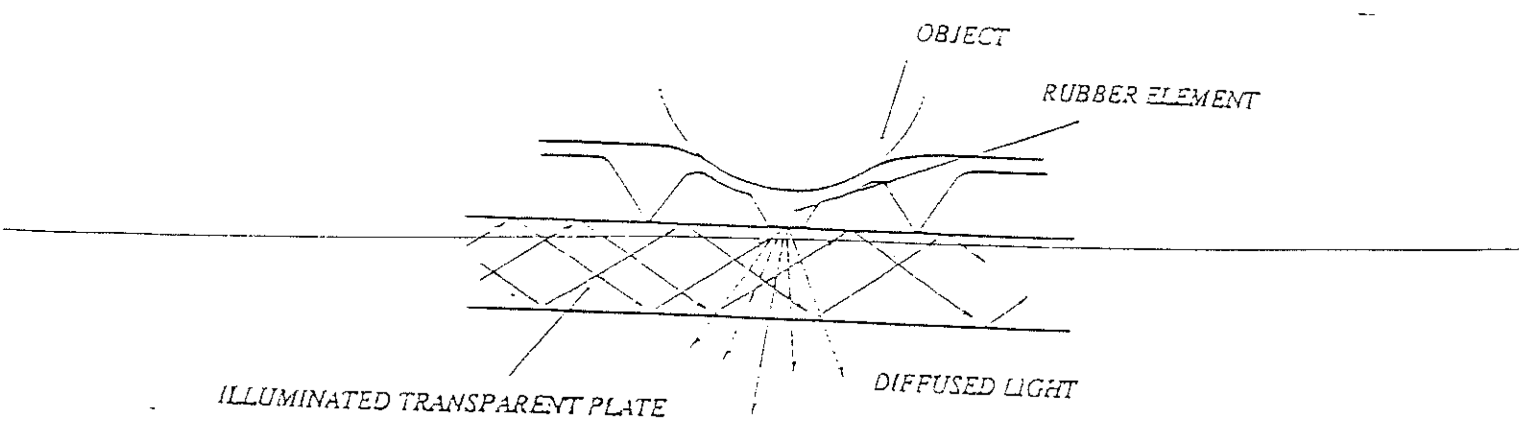


Figure 3. Contact-based frustration of total internal light reflection

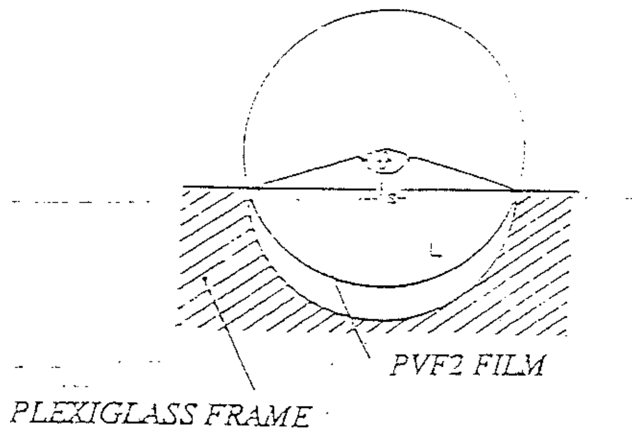


Figure 7. Cross section of a concave PVF2 US emitter

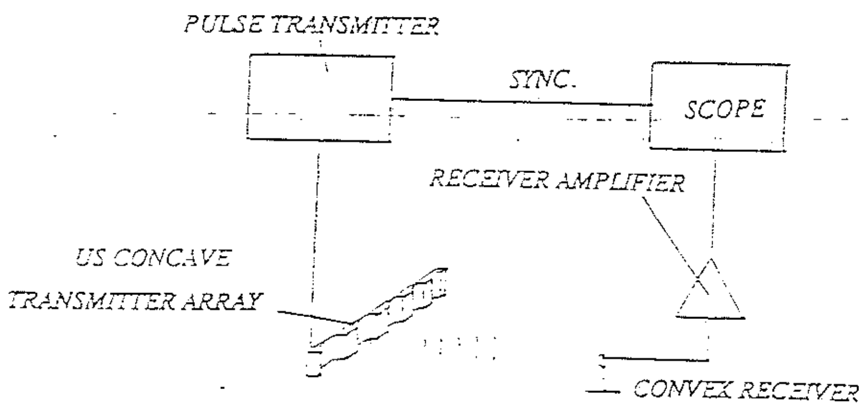
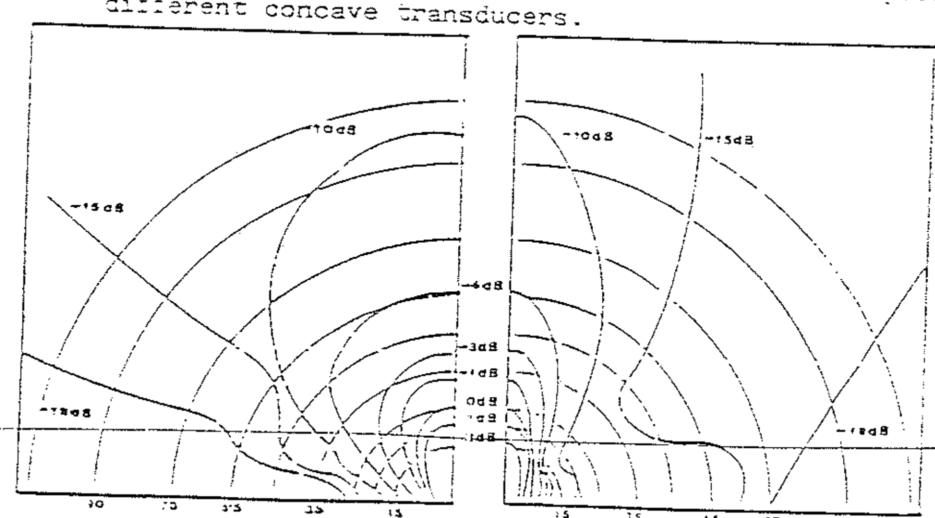


Figure 8. Experimental setup used for mapping the US field produced by different concave transducers.

(a)



(b)

Figure 9. US field intensity distribution for a convex (a) and a concave (b) PVF2 emitter, as detected experimentally with a miniature convex PVF2 receiver. The focusing effect of the concave shape is clearly visible.

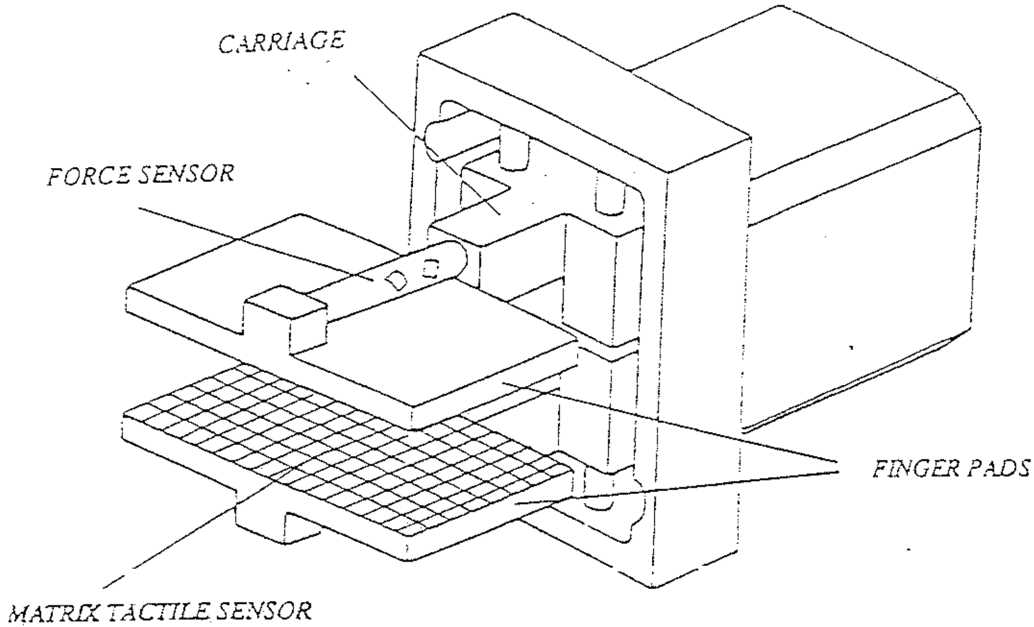


Figure 13. The parallel-jaw gripper used in our experiments: the tactile and force sensors are shown.

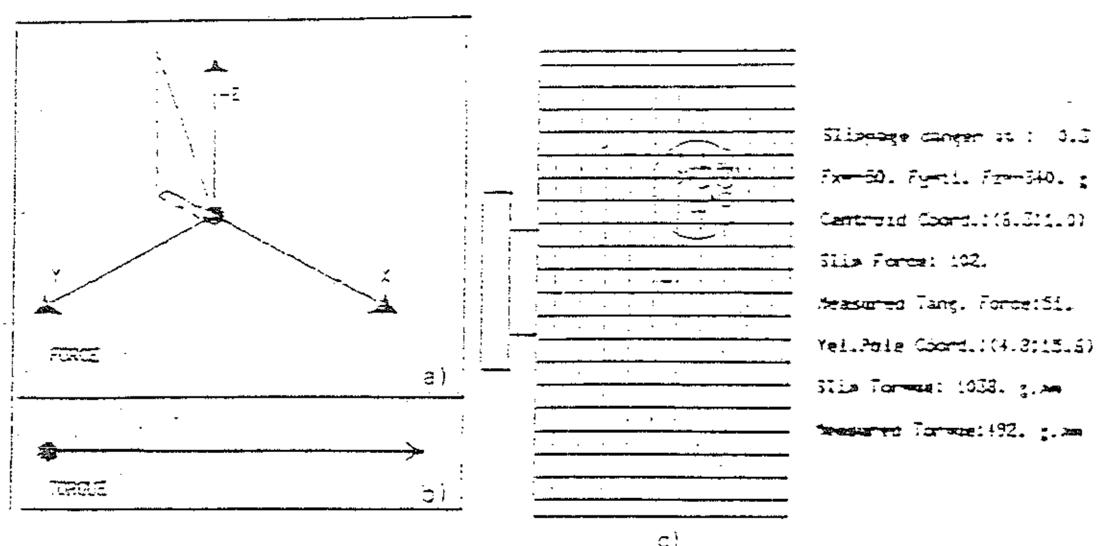


Figure 14. The experimental results illustrating the information on force a) and torque b) obtained by the force sensor, and the tactile image c) where the radius of circles on each activated tactel represents the value of maximum local tangential force.

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Dr. P. Dario
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Dear Dr. Dario:

Your paper entitled

Multiple Sensing for Dexterous End Effectors

has been accepted for presentation at the NATO ARW on "Robots with Redundancy" in Salo, Italy, on June 27-July 1, 1988. For each paper, 30 minutes is allocated at the workshop. Please plan for 20-25 minutes presentation plus 5-10 minutes discussion. Overhead projector and 35mm slide projector will be available for your presentation.

Enclosed is (i) a copy of the final program, (ii) a brochure of the hotel, (iii) local map, (iv) information on local travel and hotel accommodation, and (v) a registration form. Please return the registration form to the indicated address by June 10, 1988. You are scheduled to stay at Hotel Laurin where the workshop will be held.

Please bring with you 70 copies of the final draft of your full paper for distribution at the workshop. The editorial board's comments on your paper for inclusion in the Proceedings to be published by Springer Verlag will be based on your final draft. You will receive all information and auxiliary material regarding the preparation of your paper for the publisher at the workshop. The final camera-ready copy of your paper will be due by September 1, 1988.

Your stay at Hotel Laurin in Salo during the workshop (five nights) will be free, covered from a NATO grant. This includes room and all meals. The cost of any person accompanying you at the hotel will have to be covered by you: 105,000 lira (about $85 US) per person per night, including all meals.

I am looking forward to seeing you at the workshop.

Best regards,

Tony Bejczy

Dr. Antal K. Bejczy
ARW Director

Enclosures