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An Experiment in Manipulator Control with Proximity Sensors

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PREFACE

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory. This work was supported by the Office of Life Sciences of the National Aeronautics and Space Administration under Contract NAS 7-100.

ACKNOWLEDGEMENT

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ABSTRACT

An experiment is described in which optical proximity sensors were used in a feedback loop to automatically position a manipulator hand for grasping. The experiment was a simplified one, involving two dimensional motion only. Two proximity sensors were mounted on the hand, and control signals derived from their outputs were used to drive the hand vertically and horizontally. The sensors employ a pulsed gallium arsenide light-emitting diode together with a silicon detector. They indicate, without contact, the approximate distance between the manipulator hand and object in the range from 5 to 12 cm. Positioning within approximately ±5 mm was observed. Extension of the technique to general three-dimensional control is briefly discussed.

I. INTRODUCTION

The purpose of this report is to describe an experiment in which proximity sensors were used in a direct feedback loop to guide a manipulator into position for grasping. The experiment was a simplified one, involving motion in two dimensions only, but it illustrates how similar techniques could be extended in the future to facilitate teleoperator or robot operations.

The manipulator technology itself is well developed and has had many routine applications, especially in nuclear hot-shops, and underwater. The related literature is extensive, but the current status of manipulator and teleoperator development can be reviewed in Refs. 1 through 4. Generally, manipulation has been done using visual contact, either through a window or by means of TV, but without additional effector-mounted sensors. Some work with tactile sensing techniques has been described by Hill and co-workers (Ref. 5) and also by Goto (Ref. 6) and others (Ref. 7) in Japan. A hand-mounted optical sensor was also described by Stanford Research Institute (Ref. 8). However, there has been no previous demonstration of control by hand-mounted optical proximity sensors, which function without requiring actual contact between manipulator and object.

Although almost anything a human can do can also be done remotely by manipulator, the time required to do a given task remotely is typically one to two orders of magnitude longer than required to do the same operation manually. We believe that proximity sensing can simulate the missing sense of feel, and if the sensory information can be properly coupled into the man-machine system, significant increases in productivity will be achieved. The present experiment demonstrates an initial step toward this goal.

Specifically, a pair of optical proximity sensors were used on an experimental manipulator to guide the effector to a predetermined vertical distance from an object, under closed loop control. In addition, lateral motion was commanded by the same two sensors to center the effector above the highest point of the test object.

The following sections describe the sensors themselves, and the configuration of the sensor-equipped manipulator as used for this experiment. The results, which at this point are qualitative in nature, are described.

Finally, problems to be expected in extending the demonstrated techniques into the three dimensional world are discussed.

II. THE SENSORS

Our proximity sensors are optical devices, based on a gallium arsenide LED infrared light source and silicon detector. They have been described in an earlier report (Ref. 9). They can detect the presence of a surface within a predetermined sensitive volume, essentially by triangulation, using light reflected from the surface. In addition, they indicate the approximate distance to the surface through the magnitude of the sensor output. The distance scale over which an output is generated can be altered by the design of a replaceable external lens. The overall size of the sensor head lends itself to being mounted directly on the effector, even on the fingers themselves.

The two identical sensors used in this experiment were modified somewhat from the configuration described earlier, to satisfy the requirements of this experiment. The external lens was made plano-convex, with a spherical surface, and had a focal length of 9 cm. It was fabricated from lucite, as shown in Fig. 1, with an integral dove tail for quick replacement. This lens replaces the prism used earlier. In the present configuration the small internal lenses can be permanently focused at infinity, and need not be refocused if the focal length of the outer lens is changed.

To lengthen the sensitive region, thus obtaining a suitable range of roughly proportional response, the narrow slits were removed from the light source and detector. Each was replaced with a single knife edge, oriented as shown in Fig. 2. The knife edges are imaged in the working space in such a way that they tend to sharply cut off response beyond the focal point. Light reflected from the object is seen by the detector if the images of source and detector indicated in Fig. 2 overlap, which occurs if the surface is closer than the focal distance shown. A continuously increasing output is observed as the object is moved toward the sensor from the focal point, where the image of the two knife edges coincide, because increasing areas of the light source and detector images overlap.

The observed output voltage as a function of distance is shown in Fig. 3. The output is sufficiently well-behaved in the range from 6 cm to 12 cm to be useful for control. An approach closer than the location of the peak output at 5 cm must be avoided because of possible instability.

III. THE EXPERIMENT

The two proximity sensors were mounted on the effector (hand) of an experimental manipulator (Ref. 3, p. 74) as shown in Fig. 4. The sensitive volumes were placed about 3 cm each side of the central plane of the finger action, and just below the fingertips. The output of a sensor is thus a measure of the vertical (Z in Fig. 4) distance to the work surface, along the axis of the sensor. Increasing output indicates closer approach, as seen in Fig. 3.

The manipulator was manually operated in a rate mode with individual controls for each joint. For this experiment, the appropriate manual inputs were simply switched out and replaced with sensor signals. A more effective way of utilizing the sensor signals in a real application is suggested in the following discussion. Vertical motion was controlled by a signal obtained by comparing the sum of the two sensor outputs with an adjustable reference indicated in Fig. 3 by V_o. The control loop was arranged to move the hand such that the sensor output was driven toward the reference level, V_o. Thus, the hand is forced to a null position at a predetermined vertical distance from the surface under it.

Since the sensors were identical, the difference in their outputs is a measure of height difference and thus of the surface slope in the x direction. This difference was used directly to drive the hand in the x direction. The polarity was arranged to drive the hand uphill, that is toward a local maximum. Since an object of any kind resting on a surface will project above the surface, seeking a local maximum will direct the effector to a position above the object.

For an object such as a sphere or even an irregularly shaped but convex object, quite accurate positioning will occur. For more irregular shapes, for example, a bowl, a more complicated control scheme could be

considered, but this configuration would loosely track the edge of the bowl, which projects upwards.

A block diagram of the described system is given in Fig. 5.

Since the purpose of this experiment was to show feasibility of a concept, several simplifications were made. Actuation rates were kept low enough to ensure stability, motion was restricted to a vertically oriented plane, and the general joint-angle transformations were bypassed.

A specific configuration of the manipulator, shown in Fig. 6, was used to avoid the necessity of performing the joint angle transformations within the control system. This technique may be applicable to simplifying other experiments where completely unrestricted motion of the manipulator is not required, and so it will be briefly described here.

Oriented as shown, independent actuation of only one motor produces motion of the hand along one of the orthogonal x, y, z directions, in the work space. Vertical or z motion is by the shoulder lift joint, x motion is associated with shoulder rotation, and y motion with the elbow joint. If motion of the hand is restricted to a volume with linear dimensions small compared to the arm links, then the association of one motor with each orthogonal axis motion remains valid. The useful volume was of the order of a 30-cm cube.

In our experiment the sensor-derived vertical control input was fed to the shoulder lift motor, and the horizontal input to the shoulder rotation motor. The elbow joint was not energized, and motion was confined to the x-z plane. Control of motion in a plane could be based on two sensors, while full three dimensional implementation would have required four sensors.

IV. RESULTS

The observed behavior of the sensor-controlled manipulator will be described here qualitatively, with the aid of the sketches in Fig. 7.

A three minute movie entitled "Manipulator Control With Proximity Sensors" was made showing acquisition of several test objects by the sensor-controlled effector.

On energizing sensor control, the hand would be driven toward a flat work surface, stopping in stable equilibrium with fingertips just above the surface, Fig. 7a. If an object resting on the surface is encountered by one of the sensors, lateral motion immediately results, ending with the fingertips centered over the highest point of the object, Fig. 7b. The manipulator, of course, lifts if necessary to avoid contact as it centers itself over the object. With a rounded object of appropriate size for the Koelsch fingers, merely closing the fingers would result in grasping. The effector followed random motion of the object in the x-z plane, within the velocity capability of the manipulator (Fig. 7c). The observed accuracy of this positioning was approximately ±5 mm in both x and z directions.

If a sloping surface is encountered, uphill motion will result, continuing until a local high point is reached, Fig. 7d.

A unique type of instability was observed with a roughly-cubic object having the length of one side approximately equal to the spacing between the two sensed volumes. A slight motion laterally moved the sensed volume on or off the object, and, as a result, limit cycle motion of 2- to 3-cm amplitude involving both x and z was observed. A number of techniques for eliminating this type of instability are available, but investigation of them was beyond the scope of this experiment.

V. DISCUSSION

This simple two-dimensional experiment illustrates how proximity sensors might be used to guide a manipulator hand during a grasping operation. Four sensors are necessary for an analogous three-axis system. A possible configuration is indicated in Fig. 8 where the sensors are shown attached to the fingers rather than the wrist area. The sensor-determined vertical position would be derived from a summation of all four outputs. Motion in the plane perpendicular to z would depend on two independent signals obtained by subtracting the outputs of oppositely located sensors; for example, $S_x = V_1 - V_3$, $S_y = V_2 - V_4$.

Although beyond the scope of this discussion, other combinations could potentially be used to yield a control signal for finger closure, S_{cl} where

$$S_{c1} = (V_1 + V_2) - (V_3 + V_4)$$

and a wrist rotation signal S_w

$$S_w = (V_1 + V_3) - (V_2 + V_4)$$

To use a similar technique in a real application, joint-angle transformations in real time would be a necessary part of the control system. It would also be undesirable to restrict the effector orientation to the vertical alignment of Fig. 4. Allowing an arbitrary link configuration, and in addition an arbitrary effector orientation, would mean that the sensor signals, obtained in an effector-fixed coordinate system, must be processed to derive the appropriate commands for each joint motor. It is this processing that has been referred to as the joint-angle transformation problem. Normally, a small digital computer has been used in real time within the control loop to perform the necessary computations, although other means could perhaps be developed.

A second refinement desirable in a practical environment involves development of an effective technique for integrating sensor control into a system. The term "reflective control" has been used to signify an approach in which the operator-manipulator loop is left functionally undisturbed at all times, but where operator commands can be modified or over-ridden by the sensors. Some means for superimposing the operator and sensor commands and properly weighting them is required. A satisfactory solution to this problem would greatly increase the effectiveness of the sensor-manipulator combination over that available with a simple operator-controlled switchover between direct control and sensor control.

Although the differencing and amplification of two separate sensor outputs might be expected to be subject to noise problems, difficulty was not experienced, because the signal was relatively strong. However, attention was given to controlling offsets and drifts in the subtractive channel that controlled horizontal motion.

Another potential problem is that of variable reflectivity of the sensed objects themselves. Since the sensor output is based on the intensity of a light reflection, the function relating sensor output to position is dependent

on reflectivity. The objects used were of fairly uniform reflectivity. Although the system was not unduly sensitive to reflectivity; (for example, a granitic rock will serve as an object), extreme variations in reflectivity can be expected to cause errors in positioning. Two approaches can be suggested. The sensor response is partly determined by geometry and partly by the intensity of the light return. Optical modifications to increase the sharpness of the sensed volume could be made, resulting in an output tied more to the geometry built into the sensor optics. Alternatively, the sensor design could be changed to correct its response for reflectivity variations. Reflectivity variations such as one would encounter with a partially black ($R \approx 5\%$) and partially white ($R \approx 90\%$) object could be handled by one of these approaches.

However, a highly reflective mirror surface represents an extreme case. Objects reflected in the mirror would be detected rather than the mirror surface itself. Diffuse scattering from a specular surface can be well below 1%, the result being too great an intensity range for the sensing device to properly account for.

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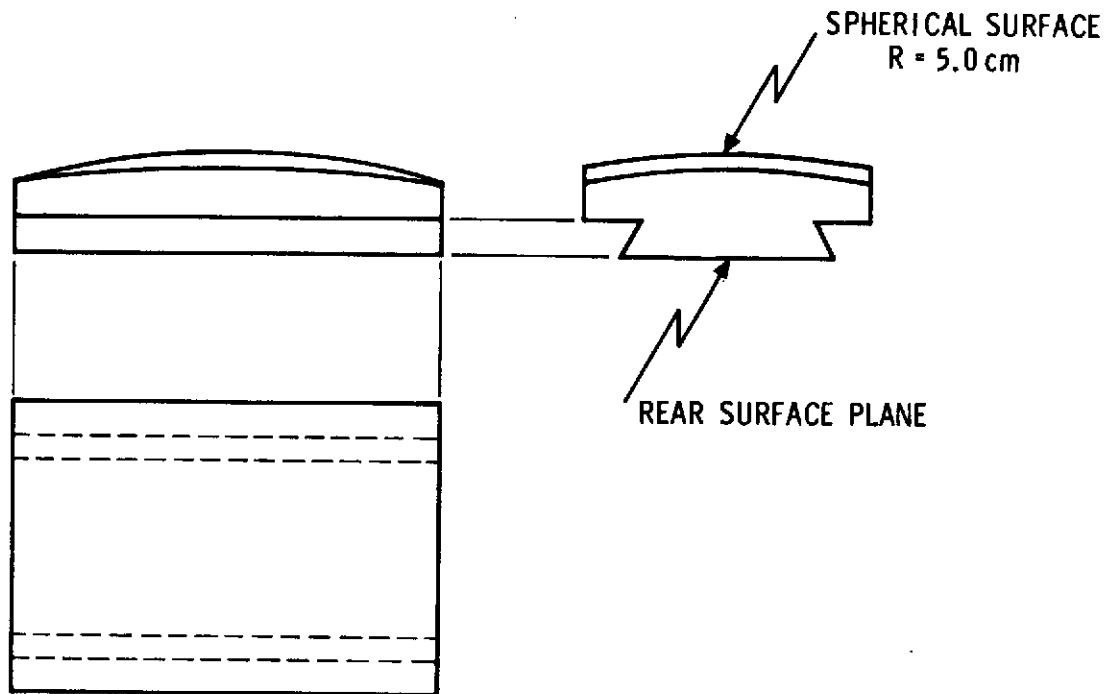
Fig. 1. Replaceable external lens of lucite used on the proximity sensor
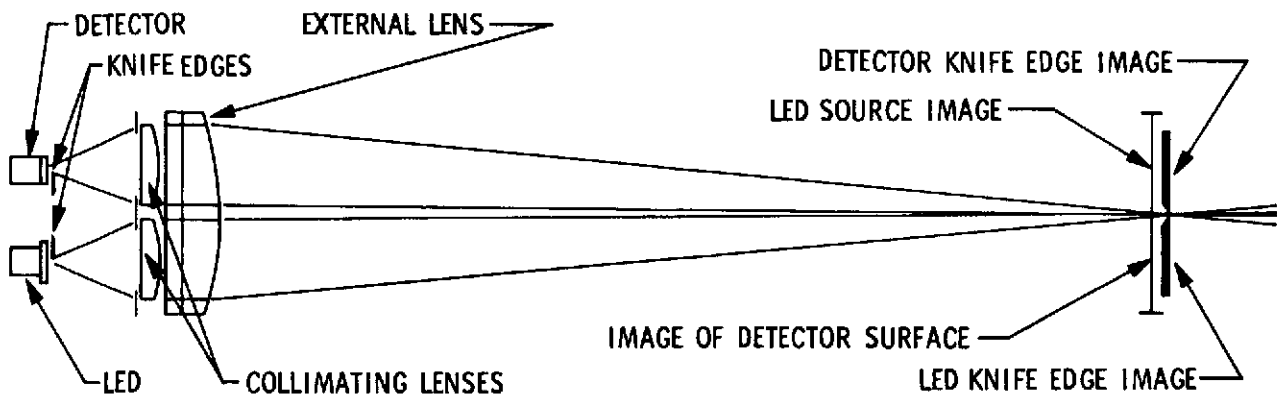

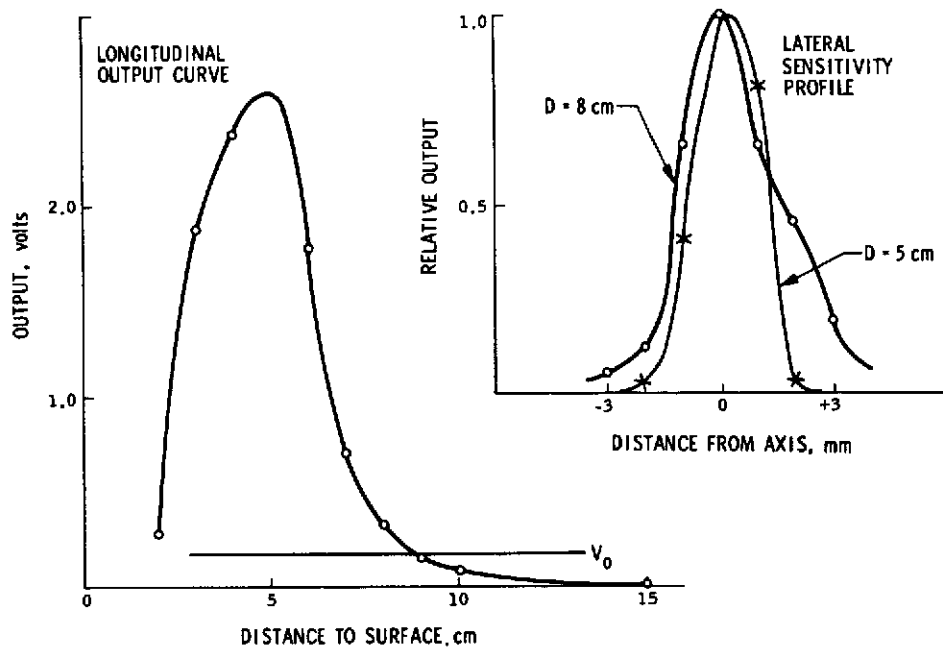Fig. 2. Internal configuration of proximity sensor showing knife edges

Fig. 3. Observed sensor output as a function of object
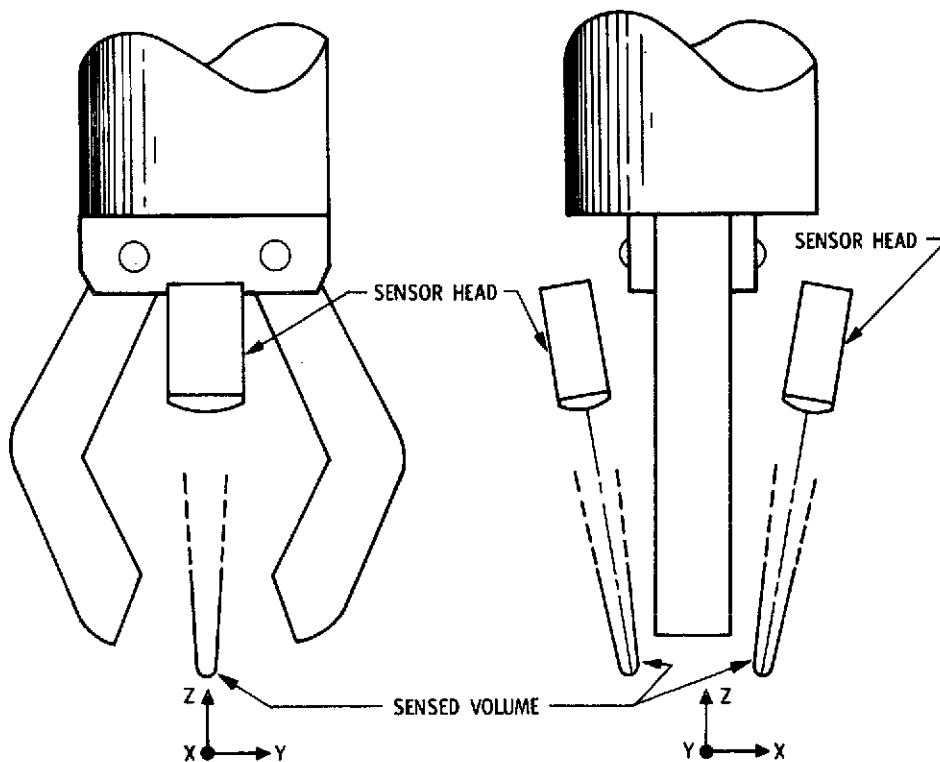position. Null point of vertical control loop
was set at V_o.

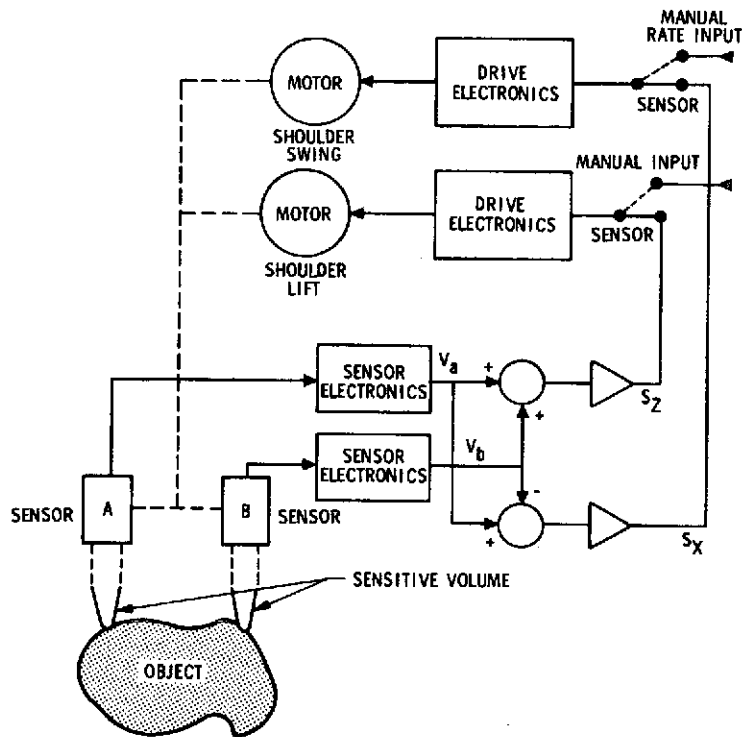Fig. 4. Sketch showing the location of sensor pair on
the Koelsch hand.

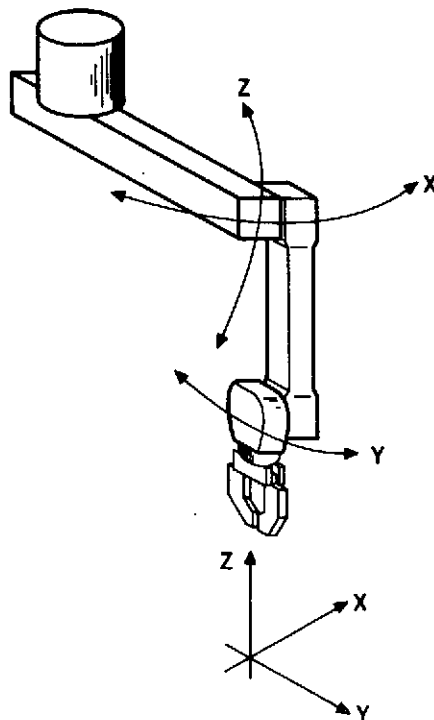Fig. 5. Block diagram of the two-axis control scheme.

Fig. 6. Configuration of the manipulator that was used to avoid the necessity of general joint angle transformations.
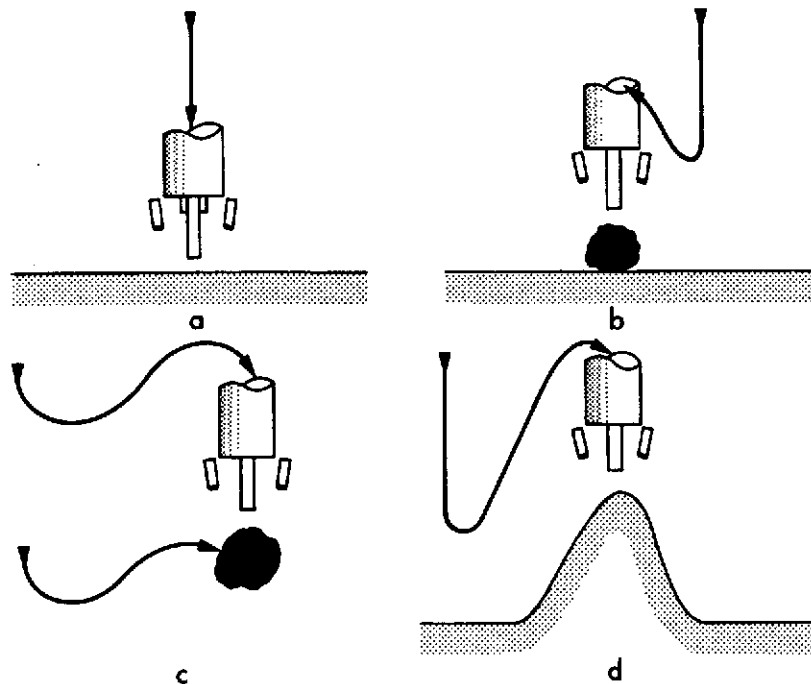
Fig. 7.   Examples of motion paths of the
         Koelsch hand under closed loop
         control.

Fig. 8.   Possible four sensor
         configuration for full
         three-axis control.