A SENSE OF TOUCH FOR A MECHANICAL HAND

by

JOSEPH J. KAPPL

Submitted in Partial Fulfillment
of the Requirements for the
Degree of Master of Science

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Signature of Author.....Signature redacted.........
Department of Mechanical Engineering

Certified by.........Signature redacted.........
Thesis Supervisor

Accepted by...............Signature redacted.......
Chairman, Departmental Committee
on Theses

DEDICATION

To my pregnant beauty

Anything for my honey

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ABSTRACT

The role of curvature of a touch surface is proposed as an important parameter of the remote manipulation situation. An optical touch sensor is conceived and evaluated. The sensor presents the curvature of the touching surface, the first derivative of that curvature and the second derivative of that curvature to the human visual sensory channel.

Thesis Supervisor: Thomas B. Sheridan

Title: Assistant Professor of Mechanical Engineering

ACKNOWLEDGEMENT

I wish to express my gratitude to Professor Thomas B. Sheridan for his guidance and encouragement throughout the course of this work. Without his help it would never have been possible.

I also wish to express my gratitude to Professor Catz for his helpful suggestions and consultations in the area of photoelasticity. In addition, I want to thank the M.I.T. Reactor Personnel, many of whom unselfishly offered themselves as subjects.

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I. INTRODUCTION

As mankind extends its sphere of influence farther and farther beyond the confines of the human body, it has an ever increasing need to make use of machines as extensions of the human body. As machines become more and more complex, there is a need to determine carefully the operational characteristics of the man-machine interface.

The field of remote manipulation must provide the answers to many questions in the area of man-machine interfaces in order to extend human control activity to the ocean floor, the surface of the moon, or outer space.

Thus far the field of remote manipulation has taken several paths of experimental investigation into the man-machine relationship. Some of these are:

1. Attempts to determine important parameters of the remote manipulation situation
2. Attempts to provide several forms of feedback to the human operator of a remote manipulator. Kinesthetic, visual and auditory types

of feedback have been used for this purpose.

3. Attempts to analyze the information content of the different kinds of feedback used.

4. Attempts to determine the engineering characteristics of the tactile sensory channel.

The instrumentation of remote manipulators with tactile sensing devices has been largely neglected for three reasons:

1. The difficulties of instrumenting the slave hand.

2. The problem of how to display the information to the operator.

3. The relatively small gain in effectiveness that might be expected if visual feedback can also be used. (1)

This work seeks to inspect the problem of instrumentation in the remote manipulation situation. It concerns the development and evaluation of an optical touch sensor.

II. PRELIMINARY INVESTIGATIONS

A. Previous Efforts

My efforts in Experimental Engineering, 2.671, an undergraduate projects course at M.I.T., were concerned with determining the mechanism of recognition through touch (2). Of the several different approaches to the problem, one seemed most fruitful. This approach consisted of placing plane geometrical shapes cut out of 3/4" plywood under a 1/2" thickness of black foam rubber. (See Fig. 1) The outer edges of the rubber mat were held against the table by means of a square framework. Subjects were then asked to identify the hidden geometrical shapes and also tell what parameters of the situation permitted identification of the objects.

Some subjects were able to identify the geometrical shapes under as many as seven 1/2" thicknesses of rubber. These subjects pointed to the changing slope pattern on the rubber as being the parameter of the situation which permitted identification of the geometrical shapes. A changing slope pattern is a curvature pattern.

Before proceeding further, it is well to point out a little more clearly what is meant by "curvature pattern". A surface can be described by

$$z = f(x,y)$$

where z is the height of a point on the surface having a particular (x,y). Consider a particular point of the surface and imagine all planes parallel to the z axis and passing through the point. Each of these planes intersects the surface in a space curve. One of these space curves has a greater curvature at the point than the other space curve intersections.

A new surface

$$\phi = g(x,y)$$

is then constructed where ϕ is the height of the surface and has a magnitude equal to the curvature of the space curve intersection on $z = f(x,y)$ that possessed the maximum curvature at the point (x,y).

On the new plane $\phi = g(x,y)$ the curve connecting points of maximum height outline the height boundary condition of $z = f(x,y)$. In the case of the foam rubber mat covering the geometrical shapes, the height boundary condition corresponds to points of contact between the rubber mat and the plywood coutout and represents the outline of the geometrical shape.

This new surface is the curvature pattern that permitted identification of the geometrical shapes. The highest point on $\phi = g(x,y)$ indicates the boundaries of the object under the mat.

Using the viewpoint that the curvature pattern is an important parameter of the touch situation, several curvature sensors were proposed which might be used to instrument a mechanical hand with a sense of touch. The curvature sensor must feed its information to some intelligence whether computer or human to be used. If a human is to receive the information contained in the curvature pattern, the receiving organ on the man side of the man-machine interface should be capable of handling the spatial aspects of the curvature pattern. The visual sensory system appears most suitable. Here it is well to point out that the curvature pattern is a form of information that is particularly suitable for human consumption.

B. An Optical Touch Sensor

During the semester that followed the completion of Experimental Engineering, 2.671, the concept of curvature as a parameter of the touch situation was discussed periodically between myself and Professor Sheridan. On one occasion he visited Professor Catz in the Experimental Stress Analysis Laboratory and was shown a sample of polyurethane rubber usually used in photoelastic stress analysis work due to its stress optical properties. The polyurethane has good transparency for thicknesses less than 1/4". One side can be painted with a reflecting paint, the opposite side supported with plexiglass plastic or Lucite, and this sandwich assembly used as a touch sensor. (See sample of rubber enclosed) Here it is possible to see the curvature of the side of the polyurethane doing the touching, from the other side. This of course is better touch curvature information than is the curvature on the back of a 1/2" thick opaque rubber mat.

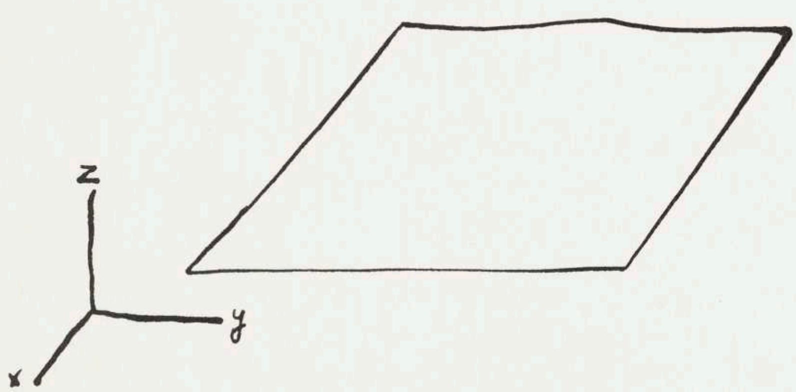
A small piece of circularly polarized polaroid sheet can be placed on the Lucite support and the sandwich assembly is now a polariscope which can detect the shear stress pattern in the polyurethane. When the sandwich assembly is used as a touch sensor, one can see both the curvature of the touching surface, and the colors indicating the shear stress caused by touch on object. A sample of polyurethane rubber and polaroid is included.

At first glance the sandwich appeared to be a pretty good touch sensor with which to instrument a remote manipulator. Here was a transducer which transformed tactile information into a form which could be fed to a human visual sensory channel and be readily used by the human to perform control tasks. This transducer permits touching objects from afar with a remote manipulator and using touch information in remote manipulation just as a human being can use his own hands as sources of touch information and use this information to manipulate objects.

Issue might well be taken with the argument that curvature pattern is a touch parameter in humans. No claim is made to this effect. My claim is rather that curvature patterns can be a useful parameter in the instrumentation of the remote manipulation situation.

III. PHYSICAL ANALYSIS OF THE TOUCH SENSOR - ROLE OF THE COLOR PATTERN

A description of deformation of the polyurethane rubber in touch situations would come from the theory of small lateral deflections of a laterally loaded flat plate. Some salient points of this theory are pointed out here so that the reader may better understand the physical situation as it relates to the touch situation.



The assumptions necessary for this analysis are:

1. Loads acting on the plate are normal to the plate surface.
2. Deflections are small compared with the thickness of the plate.

3. Reactive forces at the edges are normal to the plate.

4. Any strain in the middle plane of the plate during bending is neglected.

The differential equation of plate deflection is (Timeshenko and Woinowsky-Krieger (3))

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{q}{D}$$

where	q	- loading
	D	- flexural rigidity
	w	- vertical deflection
	z,y,x	- cartesian coordinates

Curvature is the parameter thought to be necessary for recognition of objects. In plate theory, curvature of the plate at a point is proportional to the bending moment at that point. The solution of the differential equation is

$$w = f(x,y)$$

where

$$M_x = -D\left(\frac{\partial^2 w}{\partial x^2} + \nu \frac{\partial^2 w}{\partial y^2}\right) \qquad M_y = -D\left(\frac{\partial^2 w}{\partial y^2} + \nu \frac{\partial^2 w}{\partial x^2}\right)$$

where ν - Poisson's ratio

M - bending moment

When using the circularly polarized polaroid shut with the basic sandwich assembly, a color pattern is seen. These colors are caused by the change in optical properties of the polyurethane as a result of the stress caused by touching an object. (Frocht (4))

It is well to point out that only systems of shear stresses which lie in a plane whose perpendicular is parallel with the direction ff the light ray can produce photoelastic effects.

The shear stress distribution having this orientation in the sandwich assembly is from Timoshenko and Woinowsky-Krieger.

$$\tau_{xy} = -\frac{E_z}{1+\nu} \frac{\partial^2 w}{\partial x \partial y} - \frac{E}{1-\nu^2}\left(\frac{h^2 z}{4} - \frac{2-\nu}{6} z^3\right) \frac{\partial^2}{\partial x \partial y} \Delta w$$

where E - Young's Modulus

h - thickness of plate in z direction

Δw - $\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}$

τ - shear stress

The shear stress at a particular (x,y) varies through the thickness of the plate. Therefore the color produced photoelastically is proportional to an integrated average over the thickness of the shear stress distribution

$$\text{Color} \propto \frac{1}{h}\int_{0}^{h} \tau_{xy} \, dz$$

Since shear stress is proportional to the derivative of the bending moment or curvature, the color pattern actually presents the curvature derivative pattern.

The color pattern is proportional to the stress pattern or the third derivative of the deflection pattern. Color gradient or color change is proportional to the fourth derivative of deflection. From the load-deflection differential equation, the fourth derivative of deflection is proportional to loading. There the color gradient pattern is proportional to loading.

To sum up, the basic touch sensor sandwich when used with the circularly polarized polaroid sheet, present three different informational patterns

1. Curvature pattern
2. Curvature first derivative or color patterns
3. Curvature second derivative or color gradient patterns.

IV. EXPERIMENTAL EFFORTS AND RESULTS

An attempt was made to compare the touch sensor made of polyurethane rubber, plexiglass, and polaroid sheet with the human sense of touch. Here we faced such questions as:

1. What does the human sense of touch do?
2. How could touch performance be measured?
3. What criteria of performance are suitable?

A. Recognition Experiments

It was decided that one area of comparison should be recognition of objects, and details of objects.

In this experiment the human palm, the polyurethane rubber, plexiglass sandwich, and the polyurethane rubber, plexiglass, polaroid sandwich were compared on the basis of their performance in recognition of everyday objects. The touch sensor sandwich was used with the human visual sensory channel. Subjects were taken from the engineering technician group with respect to skill and abilities.

The palm was used as the reference since it has a touch sense and closely approximates the shape size and form of the sandwich assembly. Furthermore, the palm must be moved as a unit and has little articulation. It is true that the fingertips are more sensitive than the palm but it is almost impossible to separate geometry of finger position and movement from touch phenomenon.

Three groups of 12 objects each were used so that information gained through the palm could not help identify the same objects when touched with the sandwich touch sensor.

The objects were placed on a tabletop under the palm or sandwich and the palm or sandwich lowered onto them. Subjects were permitted to roll the objects or turn them over if the objects geometrical shape permitted such movement. Subjects were not permitted to have the experimenter turn the objects over so that they might feel another side of the object.

Subjects were asked to indicate one of three levels of recognition of the object.

1. I have no idea what it is
2. I do not know what it is, but I can describe its shape

3. I know what it is and I can name it.

The subjects responses were recorded along with the time required for responses on the 12 objects in each group. Upon completion of the test, the subjects were asked several questions

1. Did the color pattern help you to identify the objects? If so, how?
2. Was the sandwich easy to use?
3. Would you rather use the touch sensor sandwich than your palm for recognition tasks?
4. Could you tell if any of the objects deformed when you touched them with the touch sensor sandwich? If so, how?

Part of the results of this experiment are shown in the table below for six subjects.

TABLE 1

	Flat Palm	Poly. Rubber & Plexiglass Sand.	Poly. Rubber Plex.& Polar.
avg time	4:57	6:57	10:01
avg mistakes	1.33	.16	.16
avg # of named objects	7.84	8.16	8.66

Recognition of objects with the flat palm was good in regard to general shape. A certain amount of small detail was not noticed, however.

Recognition via the curvature pattern of the polyurethane rubber, plexiglass sandwich was better. Subjects took longer time, made less mistakes, could discern finer detail, and could name more of the objects.

Answers to post experiment questions might be summarized as follows. Subjects generally agreed that the sandwich touch sensor was easy to use and almost all preferred to use it rather than their palms for a touch task.

Subjects who discovered or who were shown how to use the colored shear stress pattern generally agreed that the color pattern helped them recognize the objects. Subjects who were not aware of what use the color pattern could be did not think that the color pattern helped them appreciably.

Some subjects could determine if an object deformed and some subjects could not. Those who could determine deformation of an object said that the colors helped them to do so even if it was possible to determine deformation without the colors.

Most of the subjects were given some practice using the touch sensor sandwich in the following manner. The subjects practiced with some of the objects in group #1 on which they had already been run with their flat palm. Also during the touch sensor sandwich tests, the objects were shown to the subject after he had felt the object and made a response. This was done to provide some feedback to the subject concerning his performance so that he might learn as he went along. It was felt that this procedure was not necessary in the flat palm runs since each of the subjects has had many years of experience in comparing what an object feels like and what it looks like during his everyday life. Since each trial was with a new object the feedback provided no specific clue to the identification of any one object.

A second battery of tests were run using the same three groups of 12 objects each on different subjects.

The only difference from the first group of tests was that the objects were held by the experimenter. If requested to turn the objects over 90° or 180° in any direction, the experimenter did so. Allowing a subject to feel different sides of an object while attempting to recognize it seemed to be more in line with what is done in a manipulation task. The results are shown in Table 2 below for three subjects.

TABLE 2

	Flat Palm	Poly. Rubber & Plexiglass Sand.	Poly. Rubber Plex. & Polar.
avg time	6:48	11:08	10:58
avg mistakes	2.33	.33	.63
avg # of named objects	7	9.33	9.33

These results are essentially the same as the results of the first battery of tests.

Here it is well to point out the apparent approach of the subjects to the recognition task. In both batteries of tests the subjects seemed to use the information presented them by the touch sensor sandwich to build a mental image. When the image appeared to be at some level of completeness, the subject announced his recognition of the object. If the subject felt the entire object and still did not have a clear mental image, he simply felt it again until he either had a mental image he did not recognize or one that he did. In the former case he described the object, and in the latter he named the object. The cases in which the subject had no idea as to the identification of the object were few indeed.

Subjects tended to press less heavily on the objects when the polaroid sheet was used with the basic sandwich.

A subject's ability to use the touch sensor sandwich seemed to depend heavily on his facility for mental visualization.

Criteria

A subject was considered to have made an error if:

1. he misnamed the object
2. he described the object erroneously

A subject was considered not to have errored if:

1. he gave a suitable name for the object
2. he only partially described the object but was correct as far as he went
3. he had no idea what the object was

As long as a touch sensor on a remote manipulator yields information that is correct as far as it goes, one can say that it is operating properly and can be useful. However, if the touch sensor yielded information that leads to errors, or is confusing to use, serious doubts would arise as to its usefulness in manipulation.

If the touch sensor is not sensitive enough and some details of objects are missed, then of course the only solution is to engineer more sensitivity into it.

B. A Purely Tactile Task

During the course of experimentation, effort was expended toward discovering tasks which make discriminations between the tactile and other senses. As the reader can realize, a very large part of what is usually considered to be the tactile sense is really performed by the muscle sensors and tendon sensors. Discriminations of mechanical impedance and of the spatial relation between two different fingers are among such tasks.

One task was found to be particularly suited to the tactile sense. This task could not be performed by either the kinesthetic or visual senses. The task consists of determining the weight distribution of an object.

Imagine a long cylindrical rod lying on a table. When you approach the table intending to pick up the rod, your eyes note the shape of the rod and you assume mass density and weight homogeneity of the rod based on its shape. Consequently, you reach for the center of the rod, believing it to be a good vantage point from which to apply the force necessary to pick up the rod. Suppose, however, that someone has poured lead into one end of the rod giving the rod an inhomogeneous weight distribution. You will recognize the inhomogeneity of weight the moment you attempt to lift the rod.

The touch sensor sandwich can perform this task. When attempting to lift the rod which is securely held between two such touch sensor sandwiches, a moment is imposed on the reflecting side of the polyurethane rubber. This is balanced by a shear stress over a given area of the polyurethane rubber. This shear stress shows up as a number of rings of color when seen through the circularly polarized polaroid sheet. An even more sensitive indication is to watch for the development of a slight ring pattern as one starts to lift the rod. This method is a little more sensitive than two human fingers at the task of determining the center of gravity of a "leaded in one end" cylindrical rod.

It is well to point out that this capability of the tactile sense permits much more efficient use of muscular force in manipulation tasks.

C. Instrumentation of a Mechanical Hand With The Touch Sensor Sandwich

A simple mechanical hand was constructed and instrumented with a touch sensor sandwich of polyurethane rubber, an air space, plexiglass and polaroid sheet. The pattern could be transmitted back to the human operator by means of a coherent optical bundle, which yielded an image approximately equal in quality to a television picture. It was hoped that the touch sensor sandwich might be tested in actual use on a remote manipulator. While no suitable experiments were conceived or performed with the hand, various things were noticed while playing with it.

1. It is possible to determine if the object being held is slipping from the hands grasp.
2. There is some indication from the color pattern of the amount of force being used to hold the object in the hands grasp.
3. Weight distribution of a rod leaded in one end can be determined and the center of gravity can be found through the use of the hand.

4. The hand can duplicate several human motor tasks. One of these was to close one's eyes and roll a marble around on one's palm.

V. CONCLUSIONS

The results of these experiments prompts several conclusions:

1. Use of the touch sensor sandwich by a human compares favorably with a human's use of his own sense of touch.
2. Each of the different kinds of information presented by the touch sensor sandwich to the human operator can be used in various manipulation tasks.
3. The touch sensor sandwich can be a useful extension of the human tactile sense beyond the human body, namely, instrumentation for a remote manipulator.

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APPENDIX

RAW DATA

Recognition Experiment: First Battery

OBJECTS IN GROUP #1 LYING ON A TABLE TOUCHED WITH FLAT PALM

Subject	Time	Mistakes	# Objects Named
1	2:00	1	10
2	6:00	1	9
3	5:10	2	7
4	6:35	2	7
5	3:20	2	10
6	6:30	0	4

OBJECTS IN GROUP #2 LYING ON A TABLE TOUCHED WITH POLYURETHANE RUBBER, PLEXIGLASS SANDWICH

Subject	Time	Mistakes	# Objects Named
1	4:41	0	11
2	6:49	1	9
3	7:23	0	6
4	9:27	0	6
5	4:47	0	9
6	8:36	0	7

OBJECTS IN GROUP #3 LYING ON A TABLE TOUCHED WITH POLYURETHANE RUBBER PLEXIGLASS, POLAROID SANDWICH

Subject	Time	Mistakes	# Objects Named	Use Colors
1	4:00	0	12	
2	12:21	0	10	
3	12:05	0	5	No
4	9:07	0	7	
5	6:33	0	9	
6	16:03	1	10	

Recognition Experiment: Second Battery

OBJECTS IN GROUP #1 HELD IN EXPERIMENTER'S FINGERTIPS AND TURNED AT REQUEST TOUCHED WITH FLAT PALM

Subject	Time	Mistakes	# Objects Named
1	4:26	2	8
2	6:25	1	9
3	9:34	4	4

OBJECTS IN GROUP #2 HELD IN EXPERIMENTER'S FINGERTIPS AND TURNED ON REQUEST TOUCHED WITH POLYURETHANE RUBBER, PLEXIGLASS

Subject	Time	Mistakes	# Objects Named
1	10:57	0	7
2	8:53	0	12
3	13:41	1	9

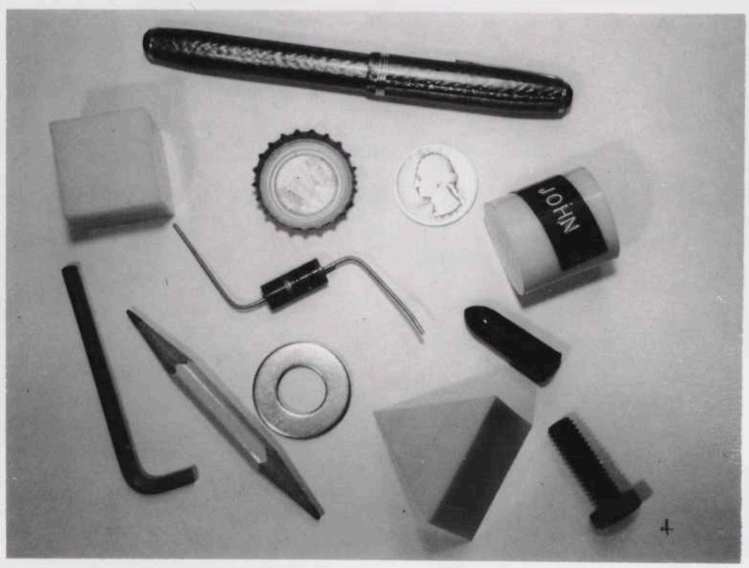
OBJECTS IN GROUP #3 HELD IN EXPERIMENTER'S FINGERTIPS AND TURNED ON REQUEST TOUCHED WITH POLYURETHANE RUBBER PLEXIGLASS, AND POLAROID

Subject	Time	Mistakes	# Objects Named	Use Colors
1	10:40	1	11	Yes
2	7:40	0	11	Yes
3	14:34	1	6	Yes

OBJECTS IN GROUP #1

Touched with ______________________________

Objects	Name	Description	No Idea
1. Bottle Cap			
2. Fountain Pen			
3. John Cylinder			
4. Large Pyramid			
5. Double Pencil			
6. Resistor			
7. Cube			
8. Quarter			
9. Hex Head Bolt			
10. Washer			
11. Pen Cap			
12. Allen Wreath			



Time

Mistakes

Remarks

OBJECTS IN GROUP #2

Touched with ________________________________

Objects	Name	Description	No Idea
1. Key			
2. Shallow Cup (2 Holes)			
3. Pencil			
4. Plastic Ball Chain			
5. Medicine Dropper			
6. Rectangular Block			
7. Paper Clip			
8. Radio Tube			
9. Sample Can Cover			
10. Nickel			
11. Small Thesis Clip			
12. Small Sphere			

Time

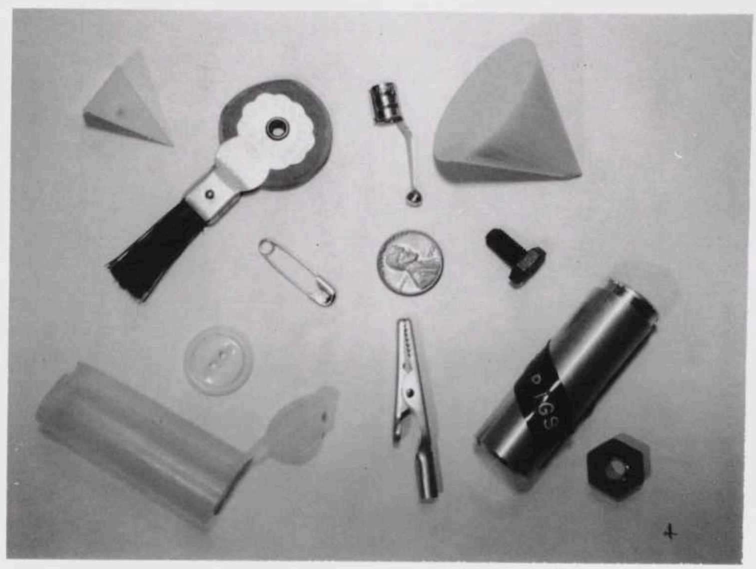
Mistakes

Remarks

OBJECTS IN GROUP #3

Touched with ______________________________

Objects	Name	Description	No Idea
1. Hex Nut			
2. Small Pyramid			
3. Type Eraser			
4. Polyvial			
5. Alligator Clip			
6. Safety Pin			
7. Small Hex Bolt			
8. Large Cone			
9. Pen Clip			
10. Three Pigs Can			
11. Penny			
12. Button			



Time

Mistakes

Remarks

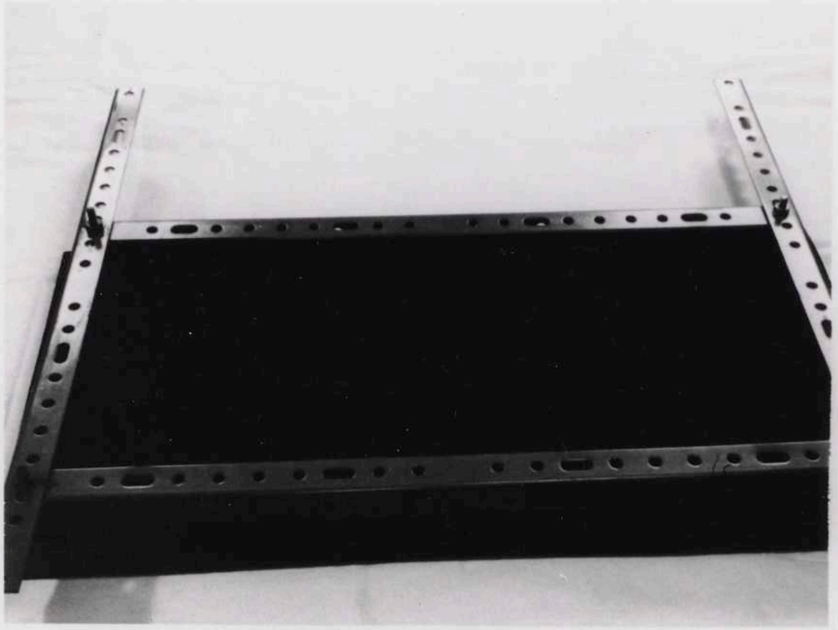


FIG. 1 Opaque black rubber mat with plywood cutout underneath. The edges are held under a square framework.

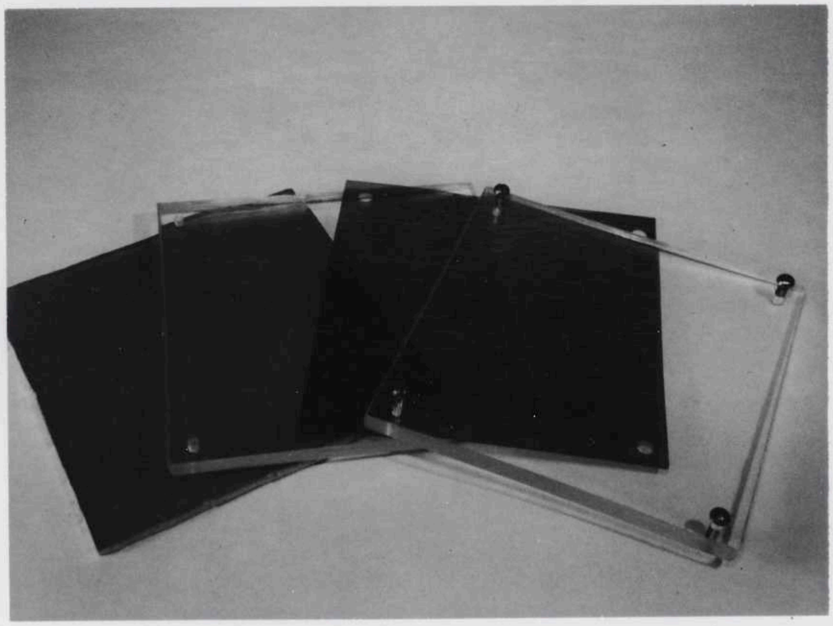


FIG. 2 Construction of the experimental sandwich touch sensor. Polyurethane, rubber, plexiglass, polaroid sheet, plexiglass.

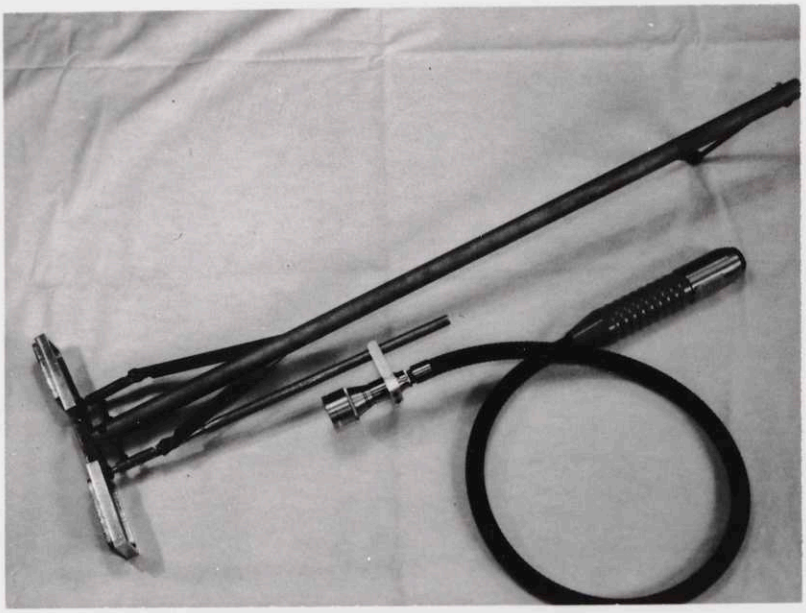


FIG. 3 A simple mechanical hand instrumented with touch sensor and coherent optical bundle transmission system.

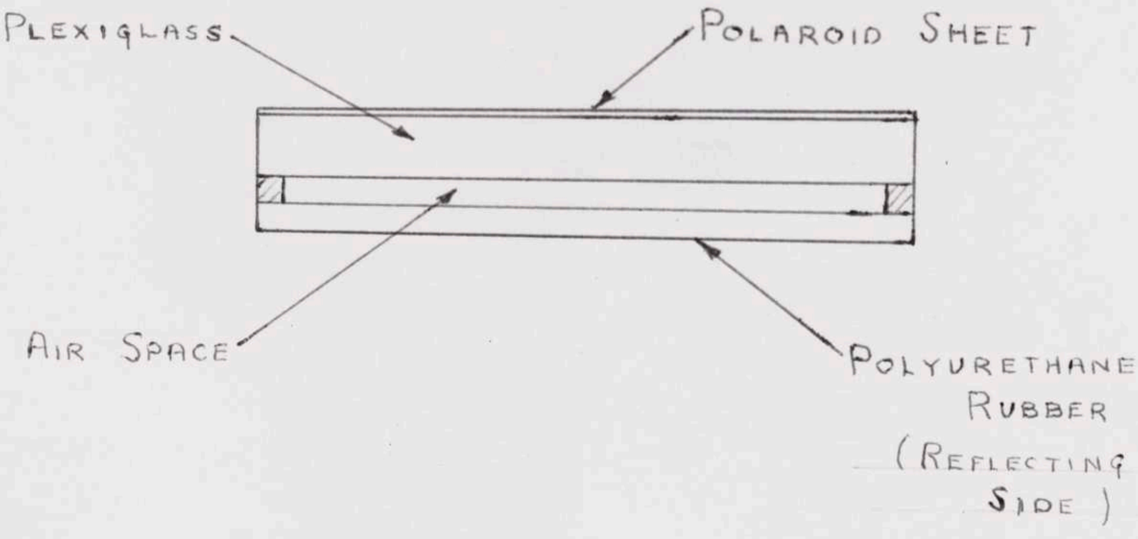


FIG. 4 Detail of touch sensor on the hand, an air space is interposed between the rubber and plexiglass. This lessens the sensitivity but widens the range so that a 3 pound brick or an egg may be handled.