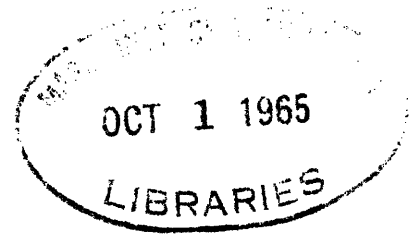


NOTICE: THIS MATERIAL MAY BE  
PROTECTED BY COPYRIGHT LAW  
(TITLE 17 US CODE)



A DYNAMIC TACTILE MATRIX OF CLOSELY SPACED PROBES

by

KAREN ELIZABETH TOMLINSON

S. B., Massachusetts Institute of Technology  
(1964)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1965

Signature of Author \_\_\_\_\_  
Department of Electrical Engineering, May 21, 1965

Certified by \_\_\_\_\_ Thesis Supervisor

Accepted by \_\_\_\_\_  
Chairman, Departmental Committee on Graduate Students

## A DYNAMIC TACTILE MATRIX OF CLOSELY SPACED PROBES

by

KAREN ELIZABETH TOMLINSON

Submitted to the Department of Electrical Engineering  
on May 21, 1965, in partial fulfillment of the requirements  
for the degree of Master of Science

## ABSTRACT

A tactile matrix of many closely spaced probes is desired for displaying two-dimensional information to blind subjects. An investigation and evaluation of possible realizations of such a matrix led to the design of a hydraulic system whose probe patterns can be set one row at a time using only row and column controls. A four-probe model and its electrical control system were constructed and tested. It was possible to set up each row of an arbitrary pattern on the model in 150 milliseconds and to hold this pattern for almost one-half minute. With a few modifications in the design, it should be possible to construct a large tactile matrix of perhaps 100 by 100 probes on a ten-inch square if sufficiently good machining techniques exist for making the necessary parts. It should be possible to change a pattern on such a matrix in less than one-half minute. Preliminary tests of the model on a blind subject indicated that such a matrix would be an acceptable display, although the noise it makes is somewhat distracting.

Thesis Supervisor: Donald E. Troxel  
Title: Assistant Professor of Electrical Engineering

## ACKNOWLEDGMENT

The author wishes especially to thank the following people who have given her valuable assistance in the execution of this thesis. Useful suggestions which are greatly appreciated were provided by them and by others in the Cognitive Information Processing Group, the Department of Electrical Engineering, and the Department of Mechanical Engineering.

Information concerning the work of the Cognitive Information Processing Group of the Research Laboratory of Electronics was provided by Prof. Samuel Mason and Prof. Donald Troxel. Special thanks is due Prof. Troxel who suggested the problem, served as thesis adviser, and made many valuable suggestions. Mr. Charles Fontaine gave helpful instruction and advice on design, construction, and use of equipment.

Especially appreciated was the work of the Research Laboratory of Electronics Machine Shop on the construction of the model. The foreman, Mr. John Keefe, gave useful advice on shop methods and capabilities. Mr. Frank Barnett used his skill and patience on the construction of the model.

Thanks is also due Mr. Roger Lucheta and Mr. Elazar Barak of the Fluid Dynamics Laboratory and the Department of Mechanical Engineering for their helpful advice on standard practices in mechanical design and mechanical drawing, and for their suggestions for improving the details of the model design. The author is especially grateful to her very good friend, Roger Lucheta, for his patience and encouragement as well as his technical advice.

The Research Laboratory of Electronics provided the materials, tools, components, and other equipment needed for this project. A National Science Foundation Fellowship made it possible for the author to undertake this year of graduate study and thesis work. This work was done in the Research Laboratory of Electronics and was supported by the Joint Services Electronics Program, the National Institutes of Health, the National Science Foundation, and the National Aeronautics and Space Administration.

## TABLE OF CONTENTS

	Page
STATEMENT OF THE PROBLEM	5
BACKGROUND OF THE PROBLEM	6
EVALUATION OF POSSIBLE SCHEMES	7
Methods of Moving the Probes	7
Logical Control of Probes	8
DESIGN OF THE MODEL	9
The Hydraulic Matrix	9
The Electrical Control System	12
Auxiliary Equipment	12
OPERATION AND EVALUATION OF THE MODEL	15
Laboratory Equipment	15
Operation of the Model	17
Suggestions for Improving the Operation of the Model	23
Evaluation of the Model	26
EXTENSION OF THE MODEL TO A LARGER MATRIX	27
BIBLIOGRAPHY	30
ILLUSTRATIONS	
Figure 1. Row and column controls in a hydraulic matrix.	10
Figure 2. Timing diagram of row and column control signals for the model.	13
Figure 3. Block diagram of electrical control system for the model.	14
Figure 4. Experimental Equipment for operating the model using a paper tape to specify the desired probe positions and to trigger control cycles.	16
Figure 5. The model with manually operated switch box to specify the desired probe positions and to trigger control cycles.	18

## A DYNAMIC TACTILE MATRIX OF CLOSELY SPACED PROBES

## STATEMENT OF THE PROBLEM

A tactile matrix display of many two-state probes which can be controlled by a minimum number of binary electrical input signals is desired as an output device for the transmission of two-dimensional information to blind subjects. Many more control signals are required if each probe is directly controlled than if some combination of row and column signals is used to control the probes so that any pattern may be set up by a sequence of control signals. Electrical control is necessary in order to have a system which can be operated by a computer for adaptive experiments or by a paper tape reader for preset experiments as well as by a human operator. This device should be capable of changing its displayed pattern fairly rapidly. For good resolution, the probes should be very close together; close spacing also reduces the area which a subject must cover with his fingers in order to observe a given number of probes. The display should be comfortable, safe, and painless to the subject; its operation should be reliable.

For example, a matrix of 100 by 100 probes on a ten-inch square (with a one-tenth inch separation between centers of adjacent probes) would be useful in the display of patterns for studies in tactile pattern recognition and in the transmission of edge-patterns of his surroundings to

a blind subject in the simulation of a mobility aid. Such a matrix would enable people to learn more about communication to human subjects via the tactile sense.

#### BACKGROUND OF THE PROBLEM

Previous attempts at making a tactile display have failed to have one or more of the properties desired in a tactile matrix of closely spaced probes. Murphy's two models<sup>1</sup>, using electromagnetic attraction caused by currents in both row and column coils to raise the probes, required shielding to prevent magnetic interaction among probes; this shielding increased the separation between adjacent probes. The smallest probe separation in his models was .45 inches. His better (more reliable) model had the further disadvantage that power dissipation in coils in the immediate vicinity of the probes caused the model to become hot. Other people<sup>2</sup> have considered various methods of displaying tactile information. The present author felt that further investigation of possible schemes for realizing the desired device would recommend at least one most promising solution, of which a small model could be built and tested.

---

1. Murphy, Ralph Allen, An Electromagnetic Pattern Simulator, Thesis (S. M.), Department of Electrical Engineering, M. I. T., September, 1964.

2. See theses in bibliography.

## EVALUATION OF POSSIBLE SCHEMES

### Methods of Moving the Probes

Any one of a variety of devices might be used to control the probes in a matrix. Magnets require extra space between the probes for shielding. Also, electromagnets produce heat. Solenoids require a larger spacing than is desired because of their size; they can not be packed to intersect a plane in the same direction with their centers as close as or less than one-half of the width of a solenoid. Closer packing would require a plunger of one solenoid to intersect the coil of another one. Since the smallest solenoids that the present author has found available are .5 inches wide, the use of such solenoids to directly operate the rods would prevent a probe separation of .25 inches or less. Of course, a matrix could be built with larger probe separation and then be funneled by flexible mechanical linkages to make a matrix with smaller separation; but it would be very difficult to maintain such a set of linkages in a matrix having many probes.

Hydraulic or pneumatic pressure and/or suction could be used to raise and lower probes (pistons) in a cylinder. Then the piston and cylinder would have to be fairly smooth and close-fitting to eliminate excessive friction and leakage. The minimum probe separation is then limited by the smallest size that one can make the cylinders and the supply lines (pressure and/or suction) connected to them.

This appears to be the most promising approach if an appropriate set of supply lines and valves can be designed and controlled without forcing the probe separation to be very large.

#### Logical Control of Probes

If a hydraulic or pneumatic scheme is used to raise and lower the probes, a reliable set of valves is needed to control the fluid flow. If the probes can be held in either position without a constant connection to a pressure or suction supply, row and column controls can be used to set up any desired pattern probe by probe. For example, a row control might connect or disconnect a cylinder and its supply line, and a column control might connect that supply line to pressure or suction reservoirs. Holding might be accomplished by an additional supply line, but this would tend to increase probe separation. If the leakages between the piston and cylinder and those through closed valves are small and if the fluid has low compressibility, it would be better to trap some of the fluid in a cylinder to hold that probe while other probes are being moved. Hydraulic oil is a good choice for the working fluid due to its low compressibility and its lubricating character; in order to be usable as a suction medium, the oil must have a low vapor pressure. Use of oil may require precautions to keep leakage from creating a mess.



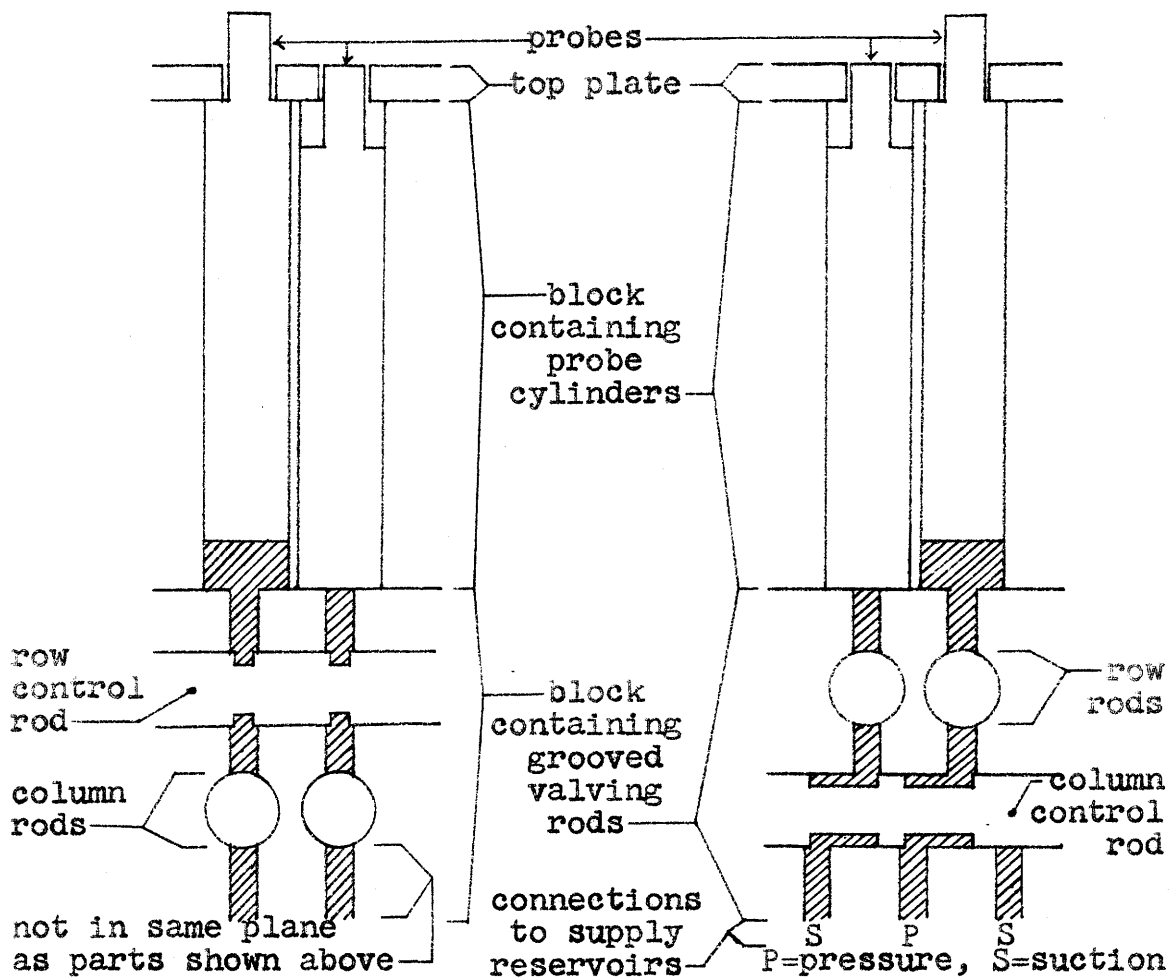
The use of this type of holding force together with ON(connect)-OFF(disconnect) row controls and PRESSURE-SUCTION column controls allows an arbitrary pattern to be set up one row at a time, as follows: set column controls for desired probe positions in row 1, turn row-1 control ON, then turn row-1 control OFF, and repeat for the successive rows. The valves of such a control system can be designed using grooved cylindrical rods which intersect channels between the supply reservoirs and the cylinders, as shown in Figure 1.

This appears to be the best method of realizing the desired matrix. It allows the probes to be closely spaced, and there is no appreciable power dissipation in the immediate vicinity of the probes. The valving rods can be moved by solenoids acting on levers connected to the ends of the valving rods. Then the solenoids need to be close together in only one direction (along the side of the matrix); they can be staggered in the other direction (normal to the plane of the display). If heating is a problem, the region containing the solenoids can be cooled without increasing the probe separation.

## DESIGN OF THE MODEL

### The Hydraulic Matrix

A four-probe hydraulic model was constructed as indicated in the previous section. Its probe separation is



1a. Row control in ON position. (Grooves are located halfway between oil lines when rod is in OFF position.)

1b. Column control in left position—to raise right probe or lower left one. (Opposite position occurs when rod is moved half of the distance between probe centers to the right—to lower right probe or raise left one.)

These cross-section drawings of a 2 x 2 matrix are approximately twice as large in each direction as corresponding parts of the model. Shaded areas represent regions which contain oil.

Figure 1. Row and column controls in a hydraulic matrix.

.25 inches. Since the purpose of the model was to test the design and since it is less difficult for a machinist to construct a model with larger probe separation, this spacing was not made smaller, although it could have been. The model was made of hardened tool steel; teflon gaskets were used between non-moving parts to prevent leakage. The design of the model is as shown in Figure 1; pressure and suction supply lines are connected to pressure and suction manifolds which are connected in turn to supply tubes at the base of the model.

Solenoid levers are each connected between a fixed point in the base plate and one end of a row or column valving rod; they fit in holes in the base plate and in holes on the undersides of collars on each end of the valving rods. Solenoids are mounted on a plate above and parallel to the base plate; those for one row and one column are mounted on the top of this plate, and the others are mounted on the bottom of the same plate. Two solenoids are used on each valving rod; each pulls the rod one way. Stops (barriers) are mounted on the model to prevent the rods from moving beyond their regions of operation.

A light-weight vacuum-pump oil was used in the matrix because of its low vapor pressure and its compatibility with the (same) oil in the vacuum pump which was used to create the suction supply.

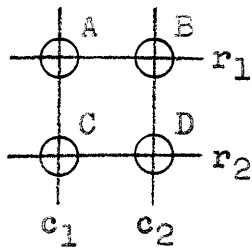
### The Electrical Control System

The control system for this four-probe model must provide control signals to the solenoid drivers in the proper time sequence which is indicated in Figure 2. The system of Figure 3 was designed and built to produce these control signals.

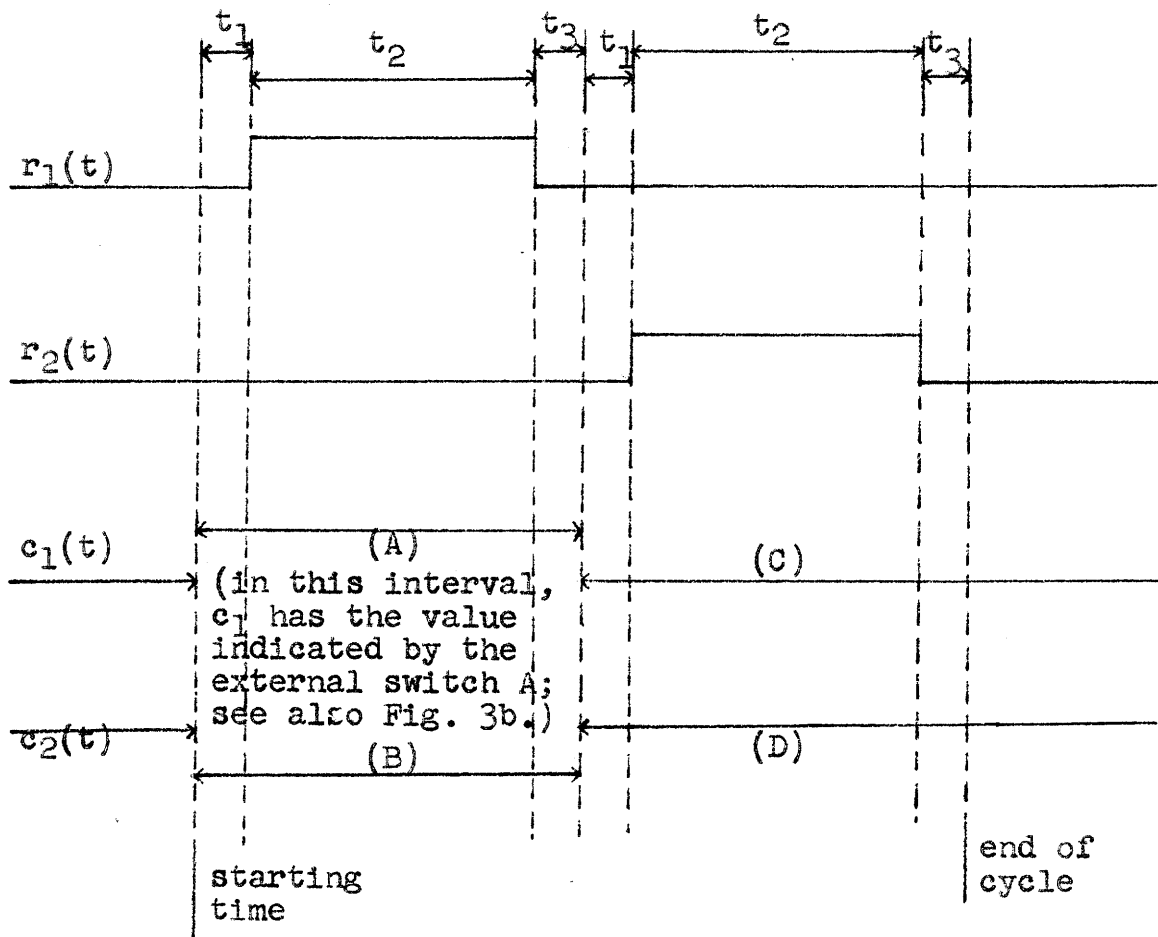
For a large matrix of  $m$  rows, the flip-flop would be replaced by a counter which would be cleared by the starting trigger and which would retrigger delay 1 each time a count signal is received if and only if the preceding count was less than  $m-1$ . Also, the combinational circuitry would be more complex.

### Auxiliary Equipment

Since air pumps were more readily available than oil pumps, the oil reservoirs consisted of two plexiglass cylinders, each containing both air and oil. The desired pressures were created by applying air pressure to one cylinder and partial vacuum to the other. A normally-closed line connecting the two cylinders was used to return oil from the suction reservoir to the pressure reservoir when the air supplies were both at atmospheric pressure. Air supplied to the cylinders was first dried (using silica gel) to prevent rusting of the model due to water in the oil lines and then filtered (through Pyrex wool and a fritted alundum cone—capable of removing particles of one-tenth micron diameter) to prevent solid particles from interfering



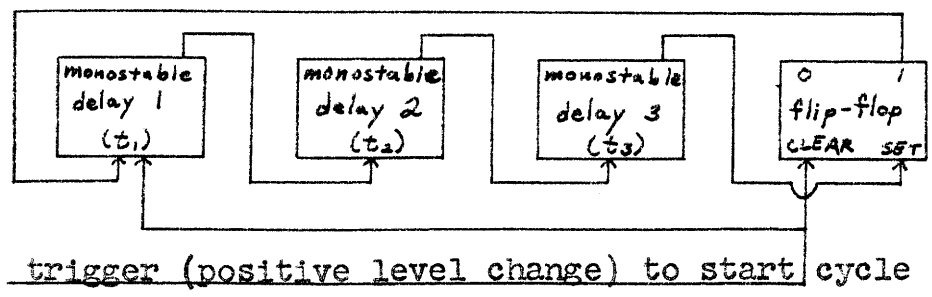
2a. Probe positions in the 2 x 2 model.



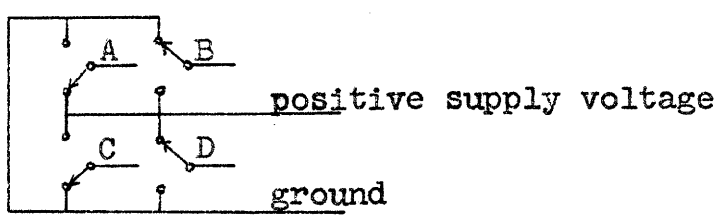
2b. Timing diagram of control signals.

(Row controls are ON for positive signal, OFF for ground signal. In row 1, column controls make connections to suction for positive signal, to pressure for ground signal; in row 2, the opposite connections are made. This inversion is due to the alternation of pressure and suction connections in adjacent rows by the column rods.)

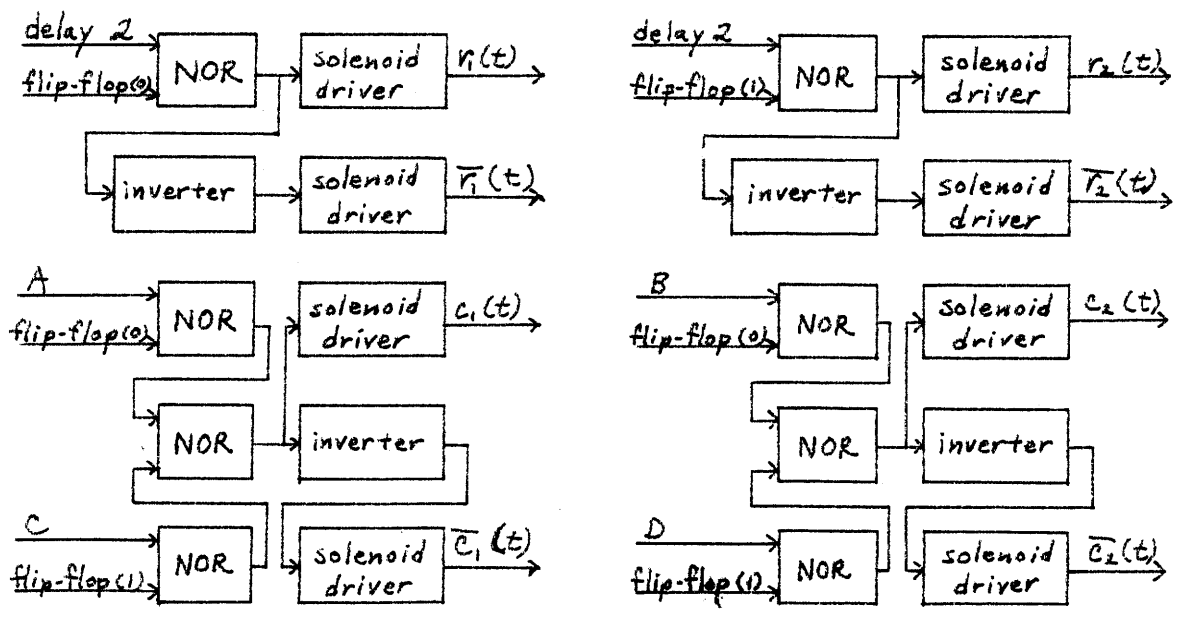
Figure 2. Timing diagram of row and column control signals for the model.



3a. The sequential circuitry.



3b. The external switches—to control the individual probes. Lower position of switch means probe is to be down; upper position of switch means probe is to be up.



3c. The combinational circuitry.

Figure 3. Block diagram of electrical control system for the model.

with the operation of moving parts. A Bourdon guage was used to measure the air pressure; a mercury manometer was used to measure the pressure drop between atmospheric pressure and the pressure in the air suction line. An oil filter (of Pyrex wool) was used in the oil supply line to remove any remaining solid particles. Tygon tubing, which is compatible with hydraulic oils, was used to make oil and air connections.

## OPERATION AND EVALUATION OF THE MODEL

### Laboratory Equipment

The experimental equipment used to operate the model from paper tape is shown in Figure 4. The auxiliary equipment for creating and measuring oil pressure and suction is mounted on the rack at the left of the picture. To the right of this rack are located, in the following order, the vacuum pump, the hydraulic model, the electrical control box, the adapter box for converting tape-reader output levels to the levels required by the electrical control system, and the paper-tape reader. Electrical power is supplied to the control system by the two power supplies on the upper shelf. Air pressure is obtained from a pressure line (not shown in the picture) on the wall.

Manual operation of the model is achieved by replacing the level adapter with the switch box. (The tape reader may also be disconnected.) A closer view of the model and the

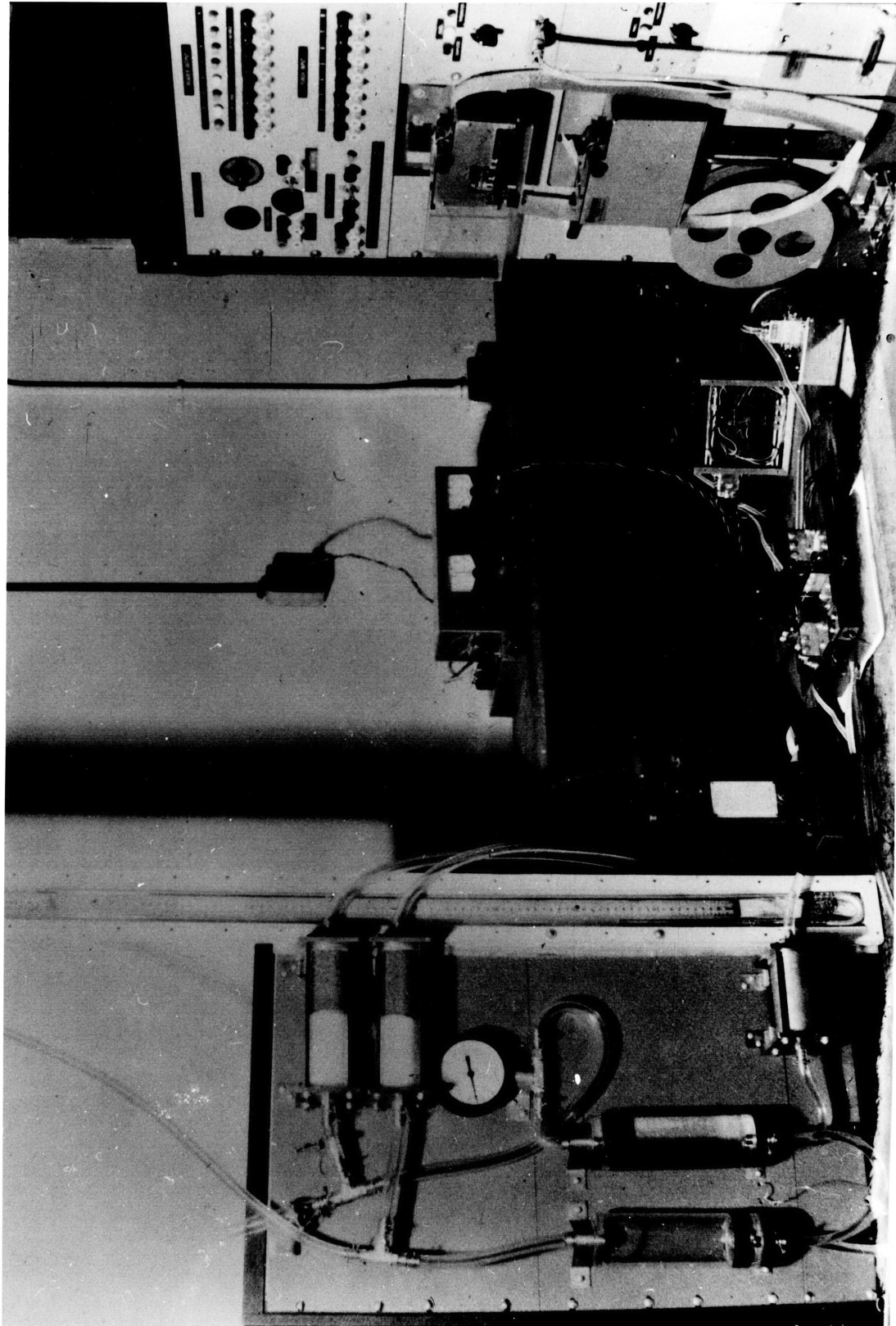


Figure 4. Experimental Equipment for operating the model using a paper tape to specify the desired probe positions and to trigger control cycles.



switch box is given in Figure 5. In this view, the probes and the valving rods are clearly visible. (The solenoids shown in Figures 4 and 5 are the larger ones mentioned in the following section.)

#### Operation of the Model

It was found that the force required to move each of the valving rods depended strongly (by as much as a factor of ten) on the rod's angular position. The angular position of each rod was therefore adjusted so that the force required to move that rod was a minimum; this minimum force varied between one and four ounces for the four rods. Also, it was found that some of the probes moved more easily in their cylinders than the others.

The tighter row rod and the tighter column rod were operated by solenoids mounted on the top of a plate and connected to the solenoid levers near the tops of those levers; the looser rods were driven by solenoids mounted on the underside of the same plate and connected to the levers at lower points on the levers. When the solenoids were positioned so that the rods could move all the way to the stops, the rods moved quite slowly and they became stuck fairly often. Some of the rods seemed to be a bit tight at one end of their operating regions; it required more force to move them from these positions than from other positions. When the solenoid positions were adjusted so that the rods

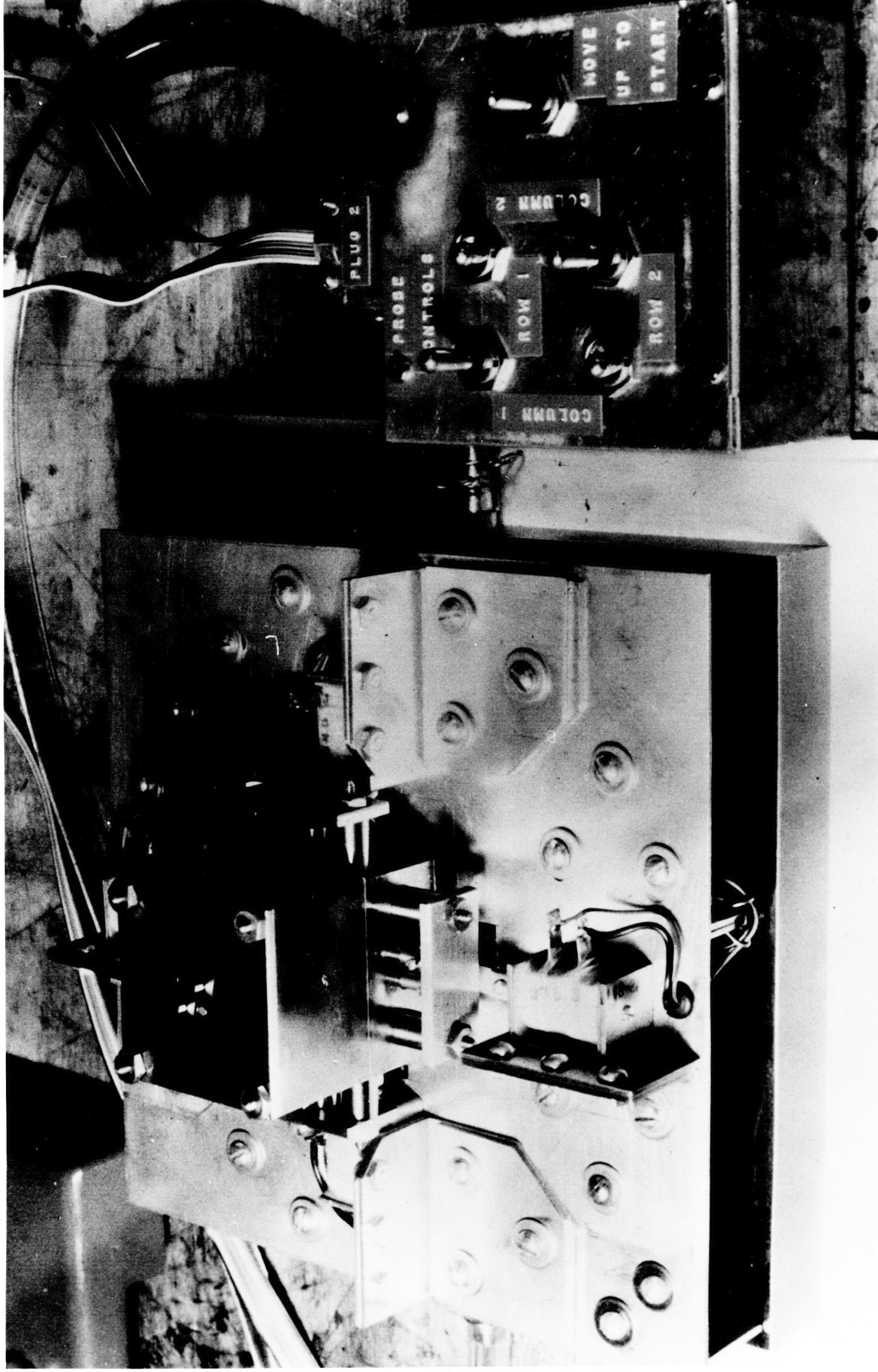


Figure 5. The model with manually operated switch box to specify the desired probe positions and to trigger control cycles.

moved a shorter distance, the model set up probe patterns more rapidly, and the rods did not get stuck as easily. Of course, shortening the distance through which the rods move tends to shorten the leakage paths so that a probe which is supposed to be held up tends to drop faster and one which should stay down tends to rise faster due to increased leakage between the cylinder and the oil supplies, along paths around a row rod which is in its OFF position and through a column rod which may be in an unfavorable position. Sticking of rods becomes more frequent after the model has been operated longer; this is probably due to slight changes in relative positions of mechanical parts, since it can be temporarily corrected by moving levers and/or solenoids slightly.

By using small solenoids on the three loosest rods and larger ones on the tightest rod, it was found that the system would operate properly with a cycle time on the order of one second; some of the rods responded rather sluggishly to control signals. When larger (stronger) solenoids were used to replace the small ones, the looser two rods did not respond as much faster as the tighter one because the lower layer of solenoids then acted at lower points on the levers, where more force must be applied in order to move the rods, because of increased solenoid width.

Low pressure differences can be used to move the probes. The slowest probe requires three seconds to be

raised one-eighth inch by a pressure of three pounds per square inch; it requires six seconds to be lowered by a suction-line pressure drop, from atmospheric pressure, of 75 millimeters of mercury. The other probes move slightly faster at these pressures.

In order to set up a pattern as fast as possible, the pressure drops between the supply lines and atmospheric pressure should be large, and the valving rods should respond quickly to their control signals. The minimum value of the time  $t_2$  (see Figure 2) is limited by the time required to raise or lower the slowest probe and thus by the available pressure drop to the suction line; minimum values of times  $t_1$  and  $t_3$  are limited by the time required to insure that the valving rods have completely responded to the preceding sequence of control signals. The maximum pressure drop which can be created in the suction line is about 70 centimeters of mercury; if the pressure drop is increased further, the oil in the suction reservoir tends to bubble into the air line and get into the filter and dryer as well as the manometer. Even if this bubbling was not a problem, the pressure drop could not be increased beyond one atmosphere, which is about 76 centimeters of mercury. This suction limit provides a lower limit of  $mt_2$  on the cycle time, where  $m$  is the number of rows in the matrix. It should be possible to move the valving rods fairly quickly

by applying large forces to push or pull the rods, so that  $t_1$  and  $t_3$  are small compared to  $t_2$ .

Operating from a paper tape which cycles the probe display through all possible patterns, the model was made to perform slightly over 200 cycles in one minute after the solenoid positions had been carefully adjusted to minimize the cycle time. The value of the cycle time was then just under 300 milliseconds; the corresponding value of  $t_2$  was found to be 116 milliseconds. For this measurement, a pressure of 14 pounds per square inch and a suction of 70 centimeters of mercury were used in the reservoirs. If any of the delays is decreased further in an attempt to decrease the cycle time, output flicker or incomplete transitions result. With these same pressures and solenoid positions, it was found that the fastest probe would drop from one eighth inch to three thirty-seconds inch in 2.5 minutes and would rise from zero to one thirty-second inch in 27 seconds when the corresponding row was turned OFF and the column controls were set to provide the worst possible leakage paths. The other probes responded much more slowly to worst-case leakage. The row rod ( $r_1$ ) corresponding to the probe (B) which responds fastest to leakage appears to be a bit too loose in the vicinity of the probes. (Probe A is lowered by leakage effects when  $r_1$  is OFF,  $c_1$  is PRESSURE, and  $c_2$  is SUCTION, so there must be a significant leakage path along rod  $r_1$ .) The other probes require more time for

the same leakage responses; the tightest two probes, both located in row 2 which also has the tightest valving rod, show no observable response to worst-case leakage in six minutes.

After the system had been operating for some time, it was found that one of the rods started sticking rather frequently. This was temporarily corrected by rotating one of the solenoid levers, which had bent slightly due to repeated use. The levers used on the model were made of .070-inch diameter steel rod; levers could have been made stronger if their cross section had been longer in the direction in which they tend to bend.

The solenoid levers were removed and the rods were connected directly to the solenoid plungers by screws to form a more rigid connection. With this arrangement, the minimum cycle time obtained was 675 milliseconds and the leakage effects were only slightly slower; the fastest probe (B) rose from zero to one thirty-second inch in 35 seconds. However, it was found that this same rise occurred in 35 seconds when the corresponding row rod was held against the stop, completely in its OFF position. The rods seemed to get stuck a bit less often than when the levers were used, but sticking became more frequent after the system had operated for a while without further mechanical adjustments.

Results of measurements of cycle time and leakage effects depended very strongly on mechanical adjustment of

parts, especially solenoid positions. It is therefore possible that the rigid coupling seemed slower than lever coupling because of such mechanical adjustments, although this is unlikely since a great deal of care was taken in both cases to achieve optimal adjustment.

External leakage is not a problem. A small amount of oil does leak from the valving rod holes, but this is only on the order of one-tenth cubic inch for a couple of hours of rapid operation. This could easily be collected in a small container under the matrix.

There is no danger of a subject accidentally changing the position of a probe. When a row rod is ON, its probes can be held down, but this requires pushing on them. If the fingers or a hand are just resting on the probes, a pressure of 14 pounds per square inch causes the probes to rise as they should, thus raising the part of the hand that is resting on them. When the row rods are OFF, it is very difficult, if not impossible, to push a probe down.

#### Suggestions for Improving the Operation of the Model

Several modifications could be made on the model which should improve its operation. Cycle time could be decreased slightly and reliability could be significantly improved by using more force to move the valving rods. One way to do this would be to use longer and stronger levers to connect solenoids to rods, and perhaps to use stronger solenoids as well. Or, it might be better to have the levers go through

the rods and to fasten solenoids above the rods so that a solenoid would need to provide less force over a greater distance of motion. Perhaps some other scheme for direct operation of the rods, such as a hydraulic one, which would allow indirect coupling of electrical control signals to valving rods, would improve the operation of this type of matrix.

The number  $m$  of rows in a matrix of this type and the fraction  $P$  of time during which an arbitrary pattern can be held without cycling are related by the ratio  $R$  of minimum time a probe holds its position (to within some specified tolerance) to the time required for setting up one row of the matrix.

$m$  = number of rows in the matrix.

$$R = \frac{\text{time in which leakage can have a significant effect.}}{\text{time required to set up one row}}$$

$$P = \frac{\text{maximum time any pattern can be held without recycling}}{\text{time in which leakage can have a significant effect}}$$

$$= 1 - \frac{\text{minimum cycle time}}{\text{time in which leakage can have a significant effect}}$$

$$P + \frac{m}{R} = 1.$$

In order to make  $m$  and/or  $P$  large,  $R$  should be made as large as possible. The denominator of  $R$  could be decreased if the slowest row rod moved faster or if the slowest probe could be moved faster for a given pressure drop. The numerator of  $R$  can be increased by making the probe which responds



fastest to worst-case leakage fit tighter in its cylinder or by making that probe's row rod fit tighter in its hole in the vicinity of that probe. (In this model, the rod for row 1 should be made to fit tighter in its hole in the vicinity of probes A and B.) If probes in one row show the effects of worst-case leakage in much less time than those in the other rows and if patterns are held for some time between cycles, leakage effects could be significantly decreased for practical purposes by modifying the control system so that the column rods are in the positions for that row during the time between cycles. In general, if the forces used to move the row rods are equal and those applied to the column rods are equal, R can be increased by making the mechanical parts more nearly uniform so that similar parts respond to identical forces in approximately equal times. This, however, is rather difficult (and expensive) to do since holes, rods, and probes must be very round and very straight as well as have constant cross-section (except for the grooves in the rods) along their lengths. If the response times of the mechanical parts vary over a wide range, separate delays could be used to provide timing for the individual rows; each of these could be adjusted to minimize the cycle time. This would make the sequential circuitry more complicated and would simplify the combinational circuitry in the control system.

Cycle time is limited by the minimum value of  $t_2$  which is in turn limited by the available suction-line pressure drop and by the distance through which the probes must move. This distance might be made smaller, perhaps one sixteenth or one thirty-second inch. This distance must be left sufficiently long so that a probe's position can easily be detected with the fingers. Shortening the distance of motion of the probes to one thirty-second inch would not allow  $t_2$  (for the model) to be less than about 30 milliseconds and probably not quite that small. The cycle time for the 2 x 2 model might then be decreased to about 100 milliseconds, but this value is on the order of a lower bound for the cycle time of such a system.

If solenoids are used to drive the rods directly, provision should be made for fine adjustment of their positions without allowing them to become loose when being adjusted. At present, they are simply bolted to a mounting plate; once loosened, they move freely within a small region.

#### Evaluation of the Model

The smallest possible cycle time for a two-row model of this type is on the order of 100 to 300 milliseconds. At a 300-millisecond cycle time, the action of the probes is not uncomfortable to observe with the fingers.

The model makes noise, primarily due to the solenoids and the stops, when it cycles. The sound produced by the

model is considerably less than that made by the tape reader, but it is enough to be distracting to a subject. The vacuum pump would also make noise if it operated continuously; however, it was found that the oil reservoirs contained enough air to hold the pressure drops very nearly constant for a large number of cycles, so that the pump and pressure supply do not need to be left on while the model is being used.

The solenoids do get quite warm, but the matrix itself does not heat appreciably; the region containing the solenoids can be cooled if this is desired.

Since the model was constructed for the purpose of testing this design, the ends of the probes were made in a cylindrical shape. Preliminary tests with a blind subject indicated that the probes would be more comfortable if their top edges were rounded. These tests also indicated that a matrix of this type would be an acceptable tactile display; its major disadvantage to the subject was its distracting noise. Some method of making the model operate more quietly would be desirable, in addition to improvement of the coupling from the electrical control signals to the valving rods.

#### EXTENSION OF THE MODEL TO A LARGER MATRIX

A larger matrix of this design could be built. Probe separation is limited by the minimum size in which the parts

can be made, especially the rods and their holes. A probe separation of one-tenth inch should be realizable without much difficulty, at least if the number of probes is not too large.

A major difficulty in the construction of a matrix of many probes is the problem of making the long thin grooved rods and their holes and finishing them so that they are very round, smooth, and straight. Part of this problem might be solved by making the valving rods in short sections and then moving them by pushing on one end or the other; in that case, the rod holes would not have to be quite as straight, and the rod sections would be much easier to construct.

The number of rows in a large matrix is limited by the ratio  $R$  which also depends on the available machining capabilities for the parts. Results of measurements on the model indicate that a matrix of roughly 180 rows might be built to operate properly if it cycles continuously and if a tolerance of one thirty-second inch is allowed on the probe positions, which are one eighth inch apart. This predicted number might be increased by the suggested improvements discussed previously for the model. Such a matrix, with one eighth inch probe transitions, might be made to cycle in  $.15m$  seconds where  $m$  is the number of rows.

Consideration should be given to the suggestions, made in a previous section, for improving the model as these also

apply to a larger matrix. Special attention should be directed toward solving the problems of noise and of coupling electrical control signals to the valving rods.

With these modifications, it should be possible (although expensive) to construct a matrix of 10 by 10 probes on a square inch or less, and perhaps even to construct a matrix of 100 by 100 probes on a ten-inch square, if sufficiently good machining techniques exist so that the necessary parts can be made. It should be possible to change the displayed pattern on a 100 x 100 model in less than one-half minute. Such a matrix would be an acceptable display and would be useful for studying the human tactile sense.

## BIBLIOGRAPHY

Books

Blackburn, John F.; Reethof, Gerard; and Shearer, J. Lowen (editors); Fluid Power Control, The Technology Press of M. I. T. and John Wiley and Sons, Inc., New York, 1960.

Fitzgerald, A. E., and Kingsley, Charles, Jr., Electric Machinery, McGraw-Hill, New York, 1961, Chapters 1 and 2 on electromechanical conversion principles.

Prandtl, Ludwig, Essentials of Fluid Dynamics, Hafner Publishing Company, New York, 1949 edition, authorized translation.

Roters, Herbert C., Electromagnetic Devices, John Wiley and Sons, Inc., New York, 1941.

Theses

Bliss, James Charles, Communication via the Kinesthetic and Tactile Senses, Thesis (PhD), Department of Electrical Engineering, M. I. T., June, 1961, pages 69-72.

Fineman, Howard E., A Design Study for an Artificial Tactile Sensory System, Thesis (SB), Department of Mechanical Engineering, M. I. T., June, 1962, pages 18-31.

Mapes, Robert Duane, Tactile Reading Aid for the Blind, Thesis (SB), Department of Mechanical Engineering, M. I. T., May, 1960, pages 9-17.

Murphy, Ralph Allen, An Electromagnetic Pattern Simulator, Thesis (SM), Department of Electrical Engineering, M. I. T., September, 1964.

Traver, Alfred Ellis, Jr., Design of a Tactile Reading Aid for the Blind, Thesis (SB), Department of Mechanical Engineering, M. I. T., May, 1961, pages 6-14.

Troxel, Donald E., Tactile Communication, Thesis (PhD), Department of Electrical Engineering, M. I. T., August, 1962, pages 22-24.