MAN-MACHINE TACTILE COMMUICATION

Man, using a simple tactile device, can feel and identify shapes and objects existing only in the memory of a computer. Possible applications are cited.

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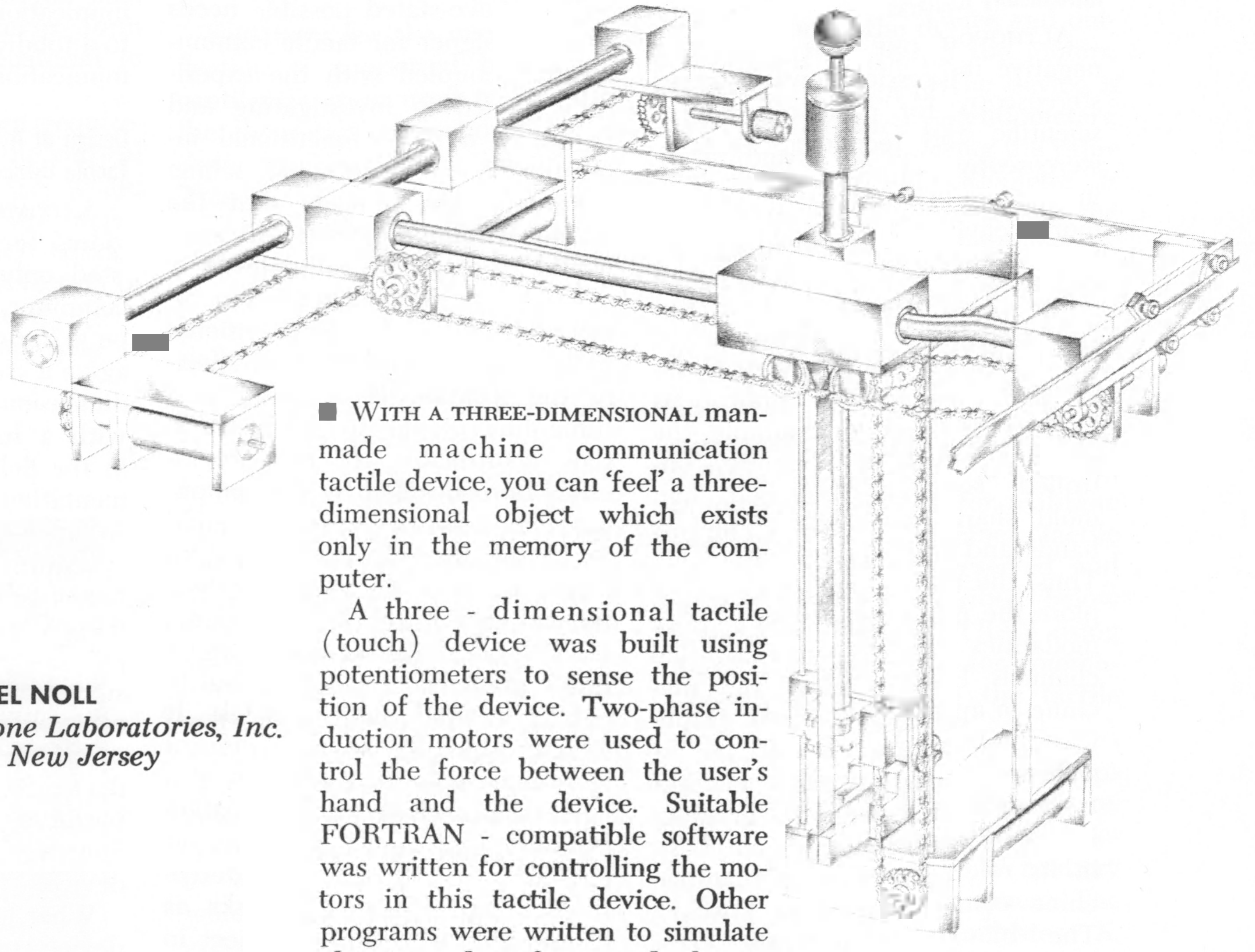

■ WITH A THREE-DIMENSIONAL man-made machine communication tactile device, you can 'feel' a three-dimensional object which exists only in the memory of the computer.

A three - dimensional tactile (touch) device was built using potentiometers to sense the position of the device. Two-phase induction motors were used to control the force between the user's hand and the device. Suitable FORTRAN - compatible software was written for controlling the motors in this tactile device. Other programs were written to simulate objects and surfaces and also to position the tactile device at a specified point.

Results thus far suggest that tactile man-machine communication is useful for "depicting" surfaces and objects which would be virtually impossible to display visually. Man-machine tactile communication also has potential as a practical scheme for computer "graphics" for the blind. In addition, the non-blind have here a possible scheme for a better and totally different "feel" for computer graphics.

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Introductory Remarks

ALTHOUGH ONE CAN JUSTIFY a negative impression towards using stereoscopy for most displays of scientific and technological data, stereoscopy sems to become more important in those fields which rely more heavily on graphical presentations, such as architecture and design.[1] However, even stereoscopic presentations sometimes do not seem sufficient for many man-machine communication applications in these fields. As an example, the designer needs a computer-controlled "something" to help him mold shapes or forms using his hands and the sensation of touch. Thus, the temptation grows to explore the potential of new sensory modalities as new communication channels between man and machine in applications where graphical communication would not be sufficient or appropriate. Perhaps the feeling that computer graphics has been given too much emphasis in its role as a form of man-machine communication is justified. The blind, for example, have learned how to develop and exploit all sorts of non-visual communication abilities so that they can live most effectively in an otherwise visually-oriented world.

The above-stated possible needs of the designer for tactile communication coupled with the experience gained in investigating and designing a three-dimensional input device for use in man-machine communication indicate that the tactile communication channel would perhaps be suitable as a new form of man-machine communication.[2] The three-dimensional input device helped the user specify the location of a point in a three-dimensional space in cartesian coordinates. If this device could be controlled by the computer so its resistance to motion could be varied, then the user would, in effect, be able to probe, by feel, the contents of a three-dimensional space. This probe would be only a single point and would be akin to poking around with a stick. It would hopefully be a significant test of the possible usefulness of a new man-machine communication channel. This tactile device could be used to augment the stereoscopic display for such tasks as latching on to a line or object in three dimensions. It could also be used in psychological investigations of interactions between the human tactile and visual communication channels. A tactile communication facility opens the door to a totally new man-machine communication channel.

Design of A Three-Dimensional Tactile Device

A COMPUTER HELPING AN individual feel some object which existed only in the memory of the computer could justifiably seem to be a "far-out" idea. One might imagine a computer-controlled, three-dimension, electromagnetic field with a hand-held ball suspended in the field as one possible implementation. But this is too esoteric. A down-to-earth hardware design is required to realistically evaluate man-machine tactile communication. Since a three-dimensional input device had already been designed and constructed, "simply" controlling the device so that the computer could vary the feel of the device, or even lock it in certain positions, seemed to be the best approach to the design of a tactile device.

What is envisioned thus far is a device consisting of a stick, free to move in three dimensions. The stick is constructed in the image of the three-dimensional input device so that motion in three dimensions has been mechanically separated. This device is shown in Fig. 1. Chains and sprocket drives of potentiometers would be used to sense the position of the stick-like portion of the device held by the user. The device might be requested to resist motion for those applications in which the user is bumping into the surface of an object. In other applications, the device might be requested to assist motion to overcome its own inertia and friction so as to move as freely as possible.

Clearly the source of force control of the device would therefore have to be able both to resist motion and to assist motion. A motor with an electrically-reversible direction of rotation meets these requirements. Three such motors connected to their own sprockets would supply the assistance or resistance to motion of the device. A linear force of about twelve pounds would be the required maximum

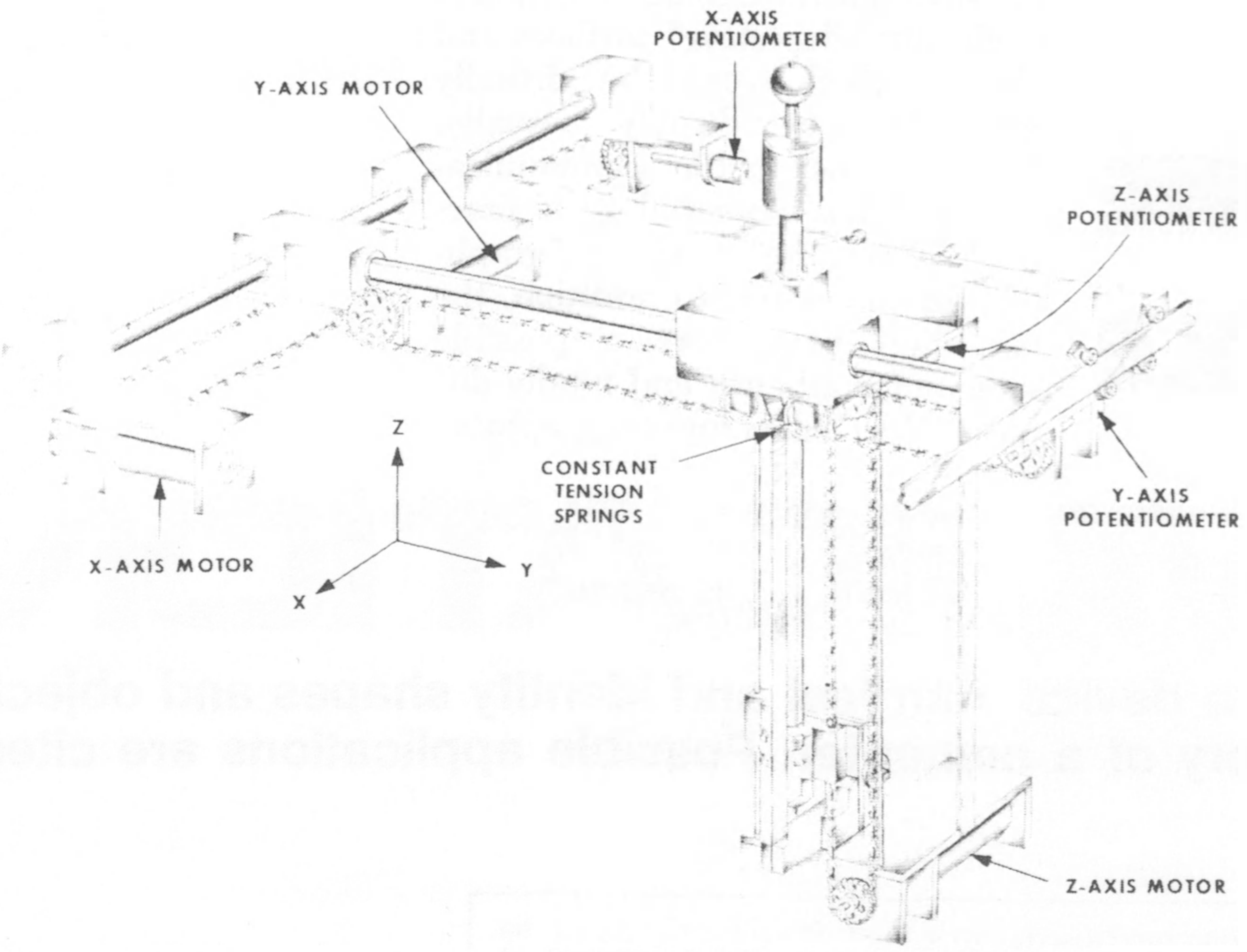

Fig. 1. Sketch of tactile device. The ball at the top of the vertical shaft can be moved within a 10-inch cubical space. The position of the ball is sensed by potentiometers while the force required to move the ball is controlled by motors.

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force to simulate bumping into a fairly rigid object. Linear bearings would be used to minimize friction. More details about the final design of this tactile device form the remainder of the material in this section.

The mechanical design requirement was imposed that the vertical shaft when fully extended would not deflect more than 0.015 inches in any direction under a maximum force of 12 pounds. A defection of 0.01 inches was determined experimentally to be just noticeable to the human hand so that this deflection requirement was most reasonable in these subjective terms.

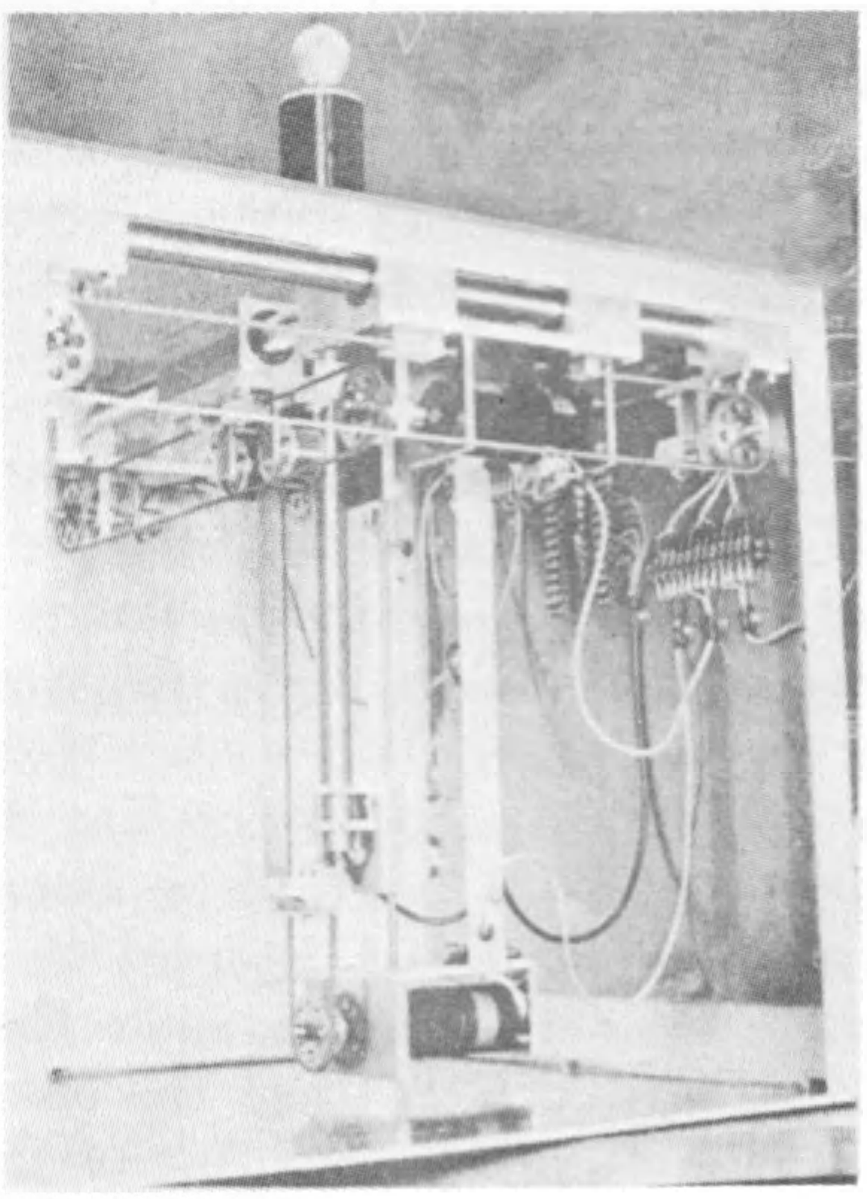

Fig. 2. Photograph of three-dimensional tactile device.

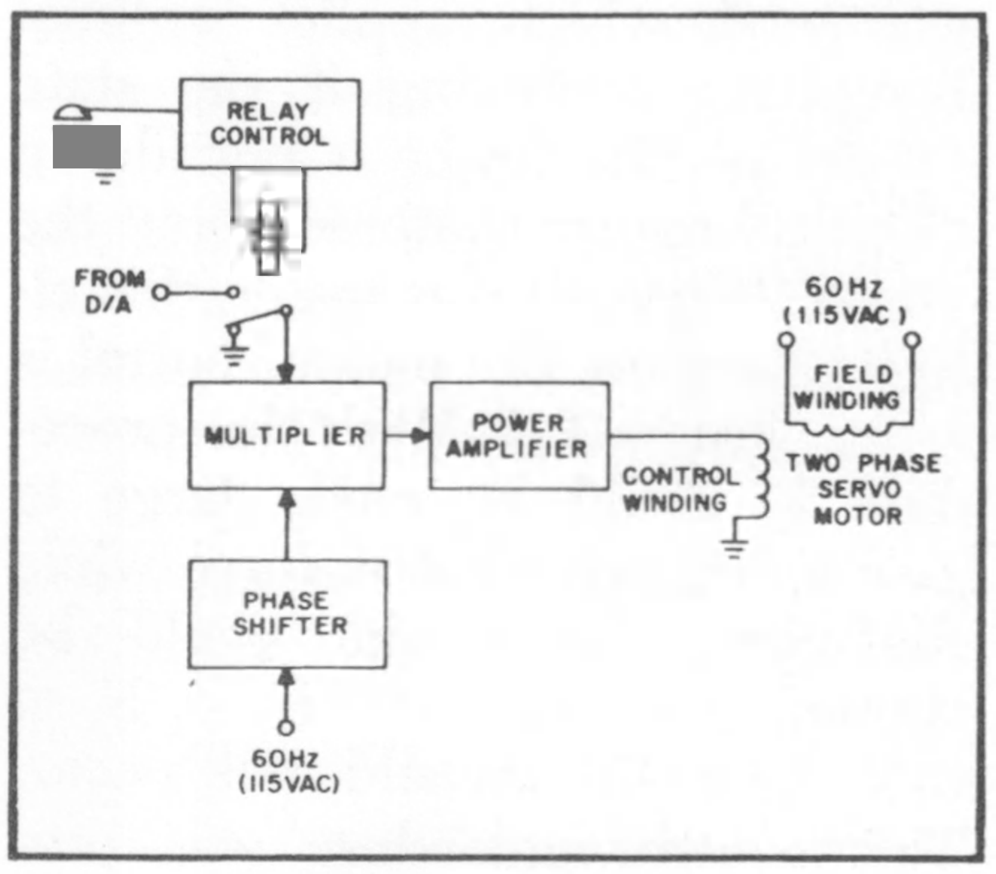

Fig. 3. Block diagram of motor control electronics. Separate phase shifters, multipliers, and power amplifiers are used for each of the three motors. The ball at the top of the tactile device has been split in half so that the user's fingers bridge the gap between the two halves and cause the relay control to operate. Thus, the user must be holding the ball for the motors to be energized.

Equations for the maximum deflection of supported beams and cantilevers were used to calculate the theoretical deflections for the device when fully extended.[3-4] This theoretical analysis indicated that the shafts forming the major structural members of the device would have to be about 1 inch in diameter to meet the maximum-deflection requirement. A photograph of the interior of the device is shown in Fig. 2.

Two-phase 60-Hz 10-watt induction motors were used to supply the forces needed to control the tactile device. The direct-current outputs from three digital-to-analog converters used to control the motors are converted to 60-Hz voltages at phases of either +90 degrees or −90 degrees depending upon the desired directions of rotation. This dc to ac conversion is accomplished by multiplying the dc voltages by 60-Hz ac voltages which have been shifted 90 degrees relative to the field winding voltages, as shown in Fig. 3. The signs of the dc voltages are retained in the multiplications so that the directions of rotation of the motors can be controlled also. Power amplifiers produce the final voltages for input to the control winding of the motors.

The ball at the top of the vertical stick has been split into two electrically-isolated halves, with the bottom half at ground potential. The upper half of the ball is connected so that when the user's fingers bridge the gap between the two halves of the ball, relays connect the inputs to the multipliers to the output from the digital-to-analog converters. This serves as a "dead-man" safety mechanism to prevent possible injury to either the user or the device, due possibly to some programming error.

Programming and Experience in Using the Tactile Device

THE SOFTWARE REQUIRED for the tactile device must simply input the position of the device and output signals to control the motors. Since the position of the device is indicated by three potentiometers, a subroutine for inputting the value of a knob or potentiometer is called three times to input the values of the three potentiometers. The motor output is accomplished by a subroutine for simply outputting three numbers to the three digital-to-analog converters which control the three motors. Thus, the guiding philosophy of FORTRAN-callable subroutines for use in FORTRAN programs for real-time interactive man-machine tactile communication was preserved, and all the program described below were written in FORTRAN using these two subroutines for communication to and from the tactile device.

One of the simplest and perhaps most basic shapes is the sphere. The tactile device was programmed to simulate a rubbery sphere suspended in space. The three-dimensional coordinates, X, Y, and Z, of the position of the tactile device were inputted to the computer which then expressed these coordinates relative to the center of the sphere. The radius R of the position of the tactile device was then computed from these coordinates. If this radius were greater than or equal to the specified radius of the sphere (R_{SPHERE}) zero force was outputted to the motors, and the device could be moved freely. If this radius were less than the radius of the sphere, forces for the three motors were computed such that the resultant force F was proportional to the square of the distance moved into the sphere until the maximum force (F_{MAX}) was attained. The square of the distance was used since this choice gives a force with a nice feel.

Second Basic Shape

A SECOND BASIC SHAPE is the cube. The program for simulating a cube was a little more involved than that for the sphere program because to compute the force the program had to know along which axis the cube was approached. The cube was suspended in the three-dimensional space such that its faces were parallel to the three axis of movement of the tactile device. Thus, it was necessary to output a non-zero force to only one of the motors to simulate bumping into a face of the cube, while zero force was outputted to the other two motors.

The cube was simulated by first inputting the three-dimensional coordinates of the tactile device. These coordinates were then expressed relative to the center of the cube. If the tactile device were outside the cube, zero force was outputted to the three motors, and the computer determined along which axis the cube was being approached. As soon as a face of the cube was entered, a force proportional to the square of the distance moved into the face was calculated until the maximum force was attained. The width of this square-law force region was variable so that the sponginess of the cube could be varied.

Users Felt Their Way Around

THE TACTILE DEVICE was programmed to simulate an object with a cubical exterior and a spherical interior. The cube and the sphere algorithms were used for these shapes. A cylindrical hole at the top of the cube allowed the user to enter the spherical interior. However, once the interior was entered through this hole, the hole was closed, and the user had to exit through a cylindrical hole in the side of the sphere. However, once the interior was exited through this hole, the hole was closed, and the user could re-enter the interior only through the hole at the top of the cube.

The cube program was modified to present a stereoscopic display of the edges of the cube and a dot representing the position of the tactile device. This was done to disprove the hypothesis that the user's "feel" of the cube would be strengthened if the user could simultaneously "see" both the cube and the position of the tactile device. Most users looked at the stereoscopic display as they "felt" the cube. But, after a short time they abandoned the display and simply felt their way around the cube by feeling the edges, falling off the edges, and sliding along the faces. Thus one quickly concludes that stereoscopic display is not necessary as an adjunct to man-machine tactile communication.

Identifying the Shapes

USERS WERE ASKED TO IDENTIFY the sphere or cube by feel alone and without being told what objects were available in the repertoire. Most users had difficulties in correctly identifying the spongy sphere although they quickly identified the cube. The major source of difficulty with the sphere was that the users nearly always slid off the surface since the sphere had a convex surface when felt from the outside. This difficulty did not occur with the sphere-within-a-cube since the inside of the sphere was a concave surface. Most users were able to explore the sphere-within-a-cube and correctly identify it along with the one-way cylindrical spaces joining the outside and inside.

Residual magnetism in the motors and leakage in the multipliers produced rotational resistance in the motors. This rotational resistance was increased by the gear train and, together with bearing friction, produced enough friction that nearly a half pound of force was required to move the tactile device. This was most bothersome to the users. Friction manifests itself in the differential equation governing motion of the device as a term proportional to velocity in a direction opposing motion. To overcome this friction, the first differences of the position of the device were computed and used as an approximation to the three-dimensional velocity of the device. These first differences were then multiplied by suitable experimentally determined constants, and the results were outputted to the motors in directions to assist movement of the device. These consants were the same for all three axes which was expected since the friction theoretically should be independent of direction. This velocity-dependent movement assist greatly increased the ease with which the device could be moved about.

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Control of the Tactile Device

IN SOME APPLICATIONS, the tactile device might be required to remain at a specified fixed location in one or more of the three dimensions. If the user attempts to move the device, a restoring force must be applied to attempt to return the device to the desired position. The determination of this restoration force is a control problem. Although considerable information is available concerning the optimal control of some device, most of this information is theoretical and avoids practical problems.[5-6] Hence, a common-sense control law, combining optimal bang-bang control and linear control, was used as described below.

Control Law

If u represents the error in position of the device and $\dot{u}$ the velocity of the device to the origin of the $(u, \dot{u})$ plane. When approaching the origin, the device has an energy $c_1\dot{u}^2 + c_2u^2$. If a linear damped control law is used in a region near the origin such that $c_1\dot{u}^2 + c_2u^2 < E_{max}$, then the energy must decrease until finally the device stabilizes at the origin. Thus, a control law was programmed which applies optimal bang-bang switching if the state $(u, \dot{u})$ of the device is outside an elliptical region centered about the origin. If the state is inside this elliptical region, the motor control is $f = -k_1u - k_2\dot{u}$. With this procedure k_1 could be made large to give a large restoration force while the energy constraint could be chosen to insure that $|f| \leq N$ so that saturation would not occur. This control procedure was programmed with the time delay correction, but the best performance was achieved by removing the delay correction. The computer plotted the state space of the device defined by u and $\dot{u}$ so c_1 and c_2 could be easily determined by varying two knobs to produce a good trajectory to the origin. If the user moves the device, his hand feels a linear restoring force. No chatter or oscillation is present.

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Future Possible Applications

THE WORK THUS FAR completed indicates that man using a conceptually simple tactile device can feel and identify shapes and objects existing only in the memory of a computer. Furthermore, the tactile device can be positioned by the computer to remain at a prescribed point. This demonstrates that the computer can be programmed to restrain the tactile device so that it can be freely moved by man over only a prescribed three-dimensional path or surface. These might seem to be meager results for extrapolating all sorts of possible future applications for tactile communication, in addition to predicting vastly more elaborate tactile communication devices. However, past experience strongly implies that science and technology have a startling ability to develop whole new fields with such unbelievable speed and in such completely unexpected ways that even the wildest extrapolations and predictions based upon present results usually seem conservative in a few years.

'Like Blind Man'

The tactile device presently constructed is concerned with computer control of the force felt at only one point within a three-dimensional space. This situation is similar to a blind person exploring and poking around three-dimensional shapes and objects with the tip of a hand-held pencil. It is most tempting to drop the pencil and grasp the object or feel the shape with one's complete hand and the tips of five human fingers. This would be possible with a computer-controlled tactile device which consisted of individual force control mechanisms for each finger and electronic or mechanical "things" for each finger tip in addition to mechanisms for controlling the overall motion of the complete hand. With such a future tactile device man could grasp objects and feel the surface texture of objects which existed only as equations or arrays of numbers in the memory of the computer.

The present and future devices for obtaining tactile communication from the computer could be augmented using a three-dimensional helmet-type display similar to that presently being used for computer-generated displays.[7] A mechanical linkage attached to the helmet senses the position of the helmet, and if the position has changed the computer recalculates the steroscopic display on the face of the two tubes. The display on the two tubes is seen by the user through half-silvered mirrors so that the external environment is also visible. In this way, the user might conceivably place his hand in the mechanism that is used for the tactile communication with the computer, and at the same time see both his hand and the computer-generated display. As an example, the user might see a computer-generated three-dimensional cube superimposed on a physical table. He could then move his hand towards the cube, feel the cube, grasp the cube through the force feedback from the tactile device, and even lift the cube from the table and feel its weight.

But what practical uses would there be for a system as elaborate as the preceding, or for that matter what possible uses would there even be for the simple man-machine tactile device described in this paper? One important use was mentioned before: namely, aiding and augmenting the "feel" of conventional man-machine communication through computer graphics so that when one latches onto an object in a display he also physically feels the latching on. Many psychological experiments come to mind that might investigate deliberately introduced clashes and offsets between the tactile and visual communication channels or the ability of a subject to identify objects by feel alone.

Hand-and-Fingers

A tactile communication device involving both the hand and the fingers would be an extremely useful design tool. With it one would be able to investigate the reaction of subjects to three-dimensional shapes and objects which could be simulated on the computer, for instance, a new design for a telephone handset. The manual dexterity of different individuals in performing assembly tasks could be scientifically investigated with computer-simulated objects, thereby resulting in an optimization of the design of an object from both an aesthetic and a functional viewpoint.

Aid to Handicapped

Perhaps the most humanistic use for a tactile communication device is as an aid for the handicapped in communicating with computers. A segment of humanity exists for whom the term "computer graphics" and all the comments about the desirability of man-machine graphical communication are completely meaningless — namely, the blind. With a tactile communication channel the blind would be able to feel the shape of graphs and other curves and surfaces and even objects. As a simple example, a blind person might hold the present tactile device while the device would be constrained by the computer so that it could be freely moved only along a prescribed three-dimensional surface or curve. If humans gifted with sight are able to identify shapes and objects by feel alone using the present tactile device, then the blind with their highly developed sense of touch and tactile memory abilities should perform significantly better.

Could 'Feel' Textiles

Perhaps the second most humanistic use for tactile communication is for communication from man to man and possibly, but not necessarily, involving computers as some form of intermediary. For this application, two humans located at two physically separate locations each with a tactile device would communicate with each other using the tactile devices and a communications network to link together the two devices. As a possible practical application a purchaser of cloth located in New York City could feel the texture of cloth produced by a textile manufacturer in Tokyo without physically transporting any cloth anywhere. A man-to-man tactile communica-

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tion facility could certainly be augmented and coupled with facilities for the transmission of sound and images. Thus, the senses of vision, hearing, and touch would have been extended over great physical distances, and "teleportation" in one sense would be closer to reality.

Future Directions of Research

A two-dimensional tactile device has been constructed by experimenters at the University of North Carolina.[8] They used their device to demonstrate that force output from the computer can help students better "visualize" concepts in elementary electromagnetic fields. The tactile device described in this paper applies reasonably large forces in three dimensions and could be used to further study the usefulness of tactile communication as an educational tool. The usefulness of man-machine tactile communication as an aid to the blind must likewise be evaluated through carefully-controlled experiments using sighted subjects as a control group. Similarly, tactile communication must be evaluated for its usefulness in supplementing three-dimensional man-machine graphical communication. A unique opportunity exists here to evaluate the effectiveness of computer graphics for man-machine communication now that an alternative form of man-machine communication has been created using the tactile device.

Psychological intersensory conflict experiments introducing deliberate distortions of the visual field have been conducted in the past.[9] With the tactile device it would become possible to introduce independent distortions between the visual channel and the tactile channel. The tactile device using a three-dimensional force-measuring mechanism to determine the force exerted by the user's hand in moving the device might be used in investigations of motor skills involving hand movement. Thus, the tactile device could easily be the common tool in a host of new areas of investigations by perceptual and motor-skill psychologists.

In the hardware area, the design and implementation of a new tactile device embodying control of the five fingers through hydraulic mechanisms would allow the user to grasp and feel objects by program control. This ability would be most useful to designers. Such a device could be used to evaluate newly designed objects by simulating the physical feel and shape of the objects.

a. Further Thoughts on Tactile Communication

THE GRAPHICAL REPRESENTATION of complicated surfaces and solid objects has always been extremely difficult even using stereoscopic techniques. Grid lines could be drawn along the surface at regular intervals or dots could be scattered at random on the surface. Either way a considerable number of points would be required to represent adequately a surface with fine or complicated details, and large numbers of points create display problems in terms of flicker and interactive problems in terms of computation time. If one portion of the surface hides another portion then yet other problems arise in terms of the suitable graphical representation of the hidden surface. A stereoscopic display of the complete surface including the hidden portion is sometimes reasonably suitable, and the depth perceptive abilities of the viewer help him to separate in depth the different portions of the surface.

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All these problems are completely circumvented when tactile communication is used to represent surfaces and objects, since the computer has to be concerned only with the position of the tactile device which is a single point in three-dimensional space. However, with a visual display the computer has to be concerned with the complete surface in all its fine and global details. With tactile communication the computer need only determine whether the tactile device is or is not "touching" the surface. The computer in effect can be concerned with all the fine details of the surface since it does not have to be concerned simultaneously with the global aspects of the surface also. Thus, tactile communication is most suitable for representing complicated surfaces and objects which would be far too detailed to represent graphically.

Man-machine tactile communication therefore emerges not as a supplement for computer-generated visual displays but primarily as an entirely-new man-machine communication medium or channel of vast importance for its own unique abilities to represent surfaces and objects. The tactile channel is a competitor to the visual channel, and this situation is something new to the field of computer science.

Epilogue

In 1932, Aldous Huxley wrote in *Brave New World* of a future entertainment medium which he called "An All-Super-Singing, Synthetic-Talking, Coloured, Stereo-

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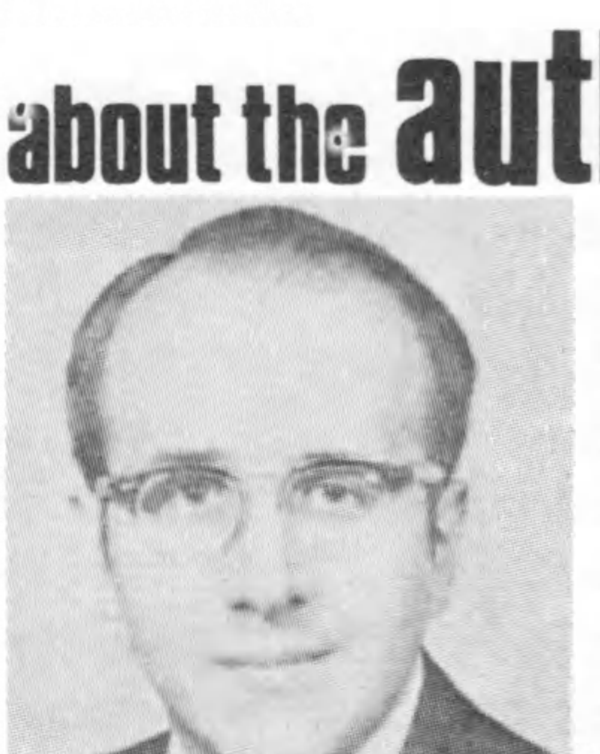
about the author



A. Michael Noll, Ph.D. (E.E.) is on the staff of the Office of Science and Technology of the Executive Office of the President, Washington, D.C., a post he came to from ten years with Bell Telephone Labs, Murray Hill (N.J.). There, he was early concerned with computer simulations and investigations of short-time spectrum analysis and the cepstrum method for vocal pitch determination. His interests also included computer-generated 3-dimensional displays of data, application of computer technology to the visual arts and psychological investigations of human reactions to pseudo-random patterns. At the time he left Bell Labs in 1971 he was exploring more effective forms of man-machine communication, including real-time 3-dimensional computer graphics and tactile communication. He has been widely published and his "computer art" has been exhibited throughout the world and shown on network television. He holds four patents in automatic speech production. He is the recipient of numerous degrees and honors. He is a native of New Jersey.

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scopic Feely."[10] Perhaps there is indeed much more truth than most scientists and technologists would admit in the claim that today's science and technology are only acting out a script written decades ago by members of the other culture. Perhaps the best visionaries in science fiction are really creative scientists and technologists who are simply far in advance of new developments in science and technology. Most certainly it would seem that the topics of computer-generated speech, real-time interactive stereoscopy, and man-machine tactile communication were all predicted forty years ago by Huxley in his "feelies."

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