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THE TACTILE ARRAY STIMULATOR

A 13-element tactile array stimulator has been developed for research into the spatial-response properties of cortical neurons in the finger areas of the somatosensory cortex, the region of the cerebrum that receives and processes the somatic senses (touch, temperature, and pain). The tactile array consists of precision limited-motion, linear-displacement motors that are individually controlled by a microprocessor-based controller.

INTRODUCTION

The sense of touch in the more highly developed mammals is very sophisticated and poorly understood. It enables us to perceive the three-dimensionality of objects we hold, to differentiate between the textures of the objects, and to perceive slippage of them. All these perceptions are derived by cortical neurons from mechanoreceptors or touch sensors found in the glabrous (hairless) skin.

The response properties of the three types of mechanoreceptors are fairly well understood:[1] Merkel's cells provide a response to continuous indentation of the skin—they respond best to low-frequency mechanical stimuli and have a peak response around 25 Hz; Meissner's corpuscles respond best to intermediate frequencies (30–40 Hz); and Pacinian corpuscles are very sensitive to high frequencies (250–300 Hz).

Although the touch sensors are fairly well understood, the real-time processing of the multiple sensor information that gives us the higher senses of touch, or perception of touch, is not understood. This lack of understanding is largely due to the lack of an effective spatiotemporal stimulator that could be used in the laboratory to easily simulate repeatable three-dimensional stimuli normally applied to the skin.

The kind of stimulator needed for laboratory purposes should be capable of creating stimuli with a resolution matching or exceeding the ability of the touch sensors to discriminate.[2] Translated into loose specifications, a stimulator should have a spatial resolution of <0.9 mm, the ability to indent the skin to a precision of <10 μm over a range of >2 mm, and a frequency response from 0 to >300 Hz. To approximate the structure of discriminable objects, a 12 by 12 array of stimulators is deemed to be minimum. Except for horizontal skin stretching, such a device should be capable of simulating most psychophysically and physiologically relevant stimulus patterns.

The most widely used tactile stimulators for psychophysical and neurophysiological research are probably those designed and built by APL's J. G. Chubbuck (retired 1986). These highly precise linear-motion motors have a resolution of 1 μm over a 2.5-mm range and a small signal bandwidth greater than 100 Hz.[3]

Their large size, however, precludes their use in a dense array.

For research requiring array stimulators, the Optacon has been the only device readily available (Telesensory Systems, Inc., Mountainview, Calif.), but it was developed to be a tactile reading aid for the blind and not a research tool. It consists of a rectangular 6 by 24 array of pins spanning an active area of 1.1 by 2.7 cm and delivering only a bi-level vibratory pattern at about 230 Hz. It does not span the range of spatiotemporal motions required of a good research tool.

The development of an appropriate research tool for spatiotemporal stimulation of the skin was started under J. G. Chubbuck in 1984 and was completed in 1986 under W. Schneider with the collaboration of K. O. Johnson of The Johns Hopkins University School of Medicine.

THE LINEAR ACTUATOR

The most important component of the tactile array stimulator is the linear-displacement motor that must be able to present a precisely controlled motion to a point on the skin via a small probe. Aside from the requirements for a large dynamic range and high bandwidth, the motor must be small enough to allow a stack of motors of manageable size to be formed into a dense array. Figure 1 shows a cross-sectional view of the motor. Like the Chubbuck motor,[3] this one also uses a moving-element mount of near-zero friction consisting of two helically slotted beryllium copper diaphragms. The diaphragms act as a spring that serves to center the motor in its motion range and also fix the shaft in rotation. The range of axial motion is limited by the end caps, which prevent the diaphragms from extending too far. (Were it not for the limitation, the motion would tend to displace the shaft radially in the direction of the diaphragms' helical arm attachment to the shaft.)

The motor's magnetic circuit consists of a high-energy-product moving magnet reacting with the fields created by two oppositely phased fixed-coil electromagnets. Hycorex 96A magnets were chosen for their high specific energy and for their resistance to demagnetization. The pole pieces and motor shell, which form the magnetic return path, are machined from Hyperco—a soft iron-

Figure 1—Cross-sectional view of the linear-displacement motor.
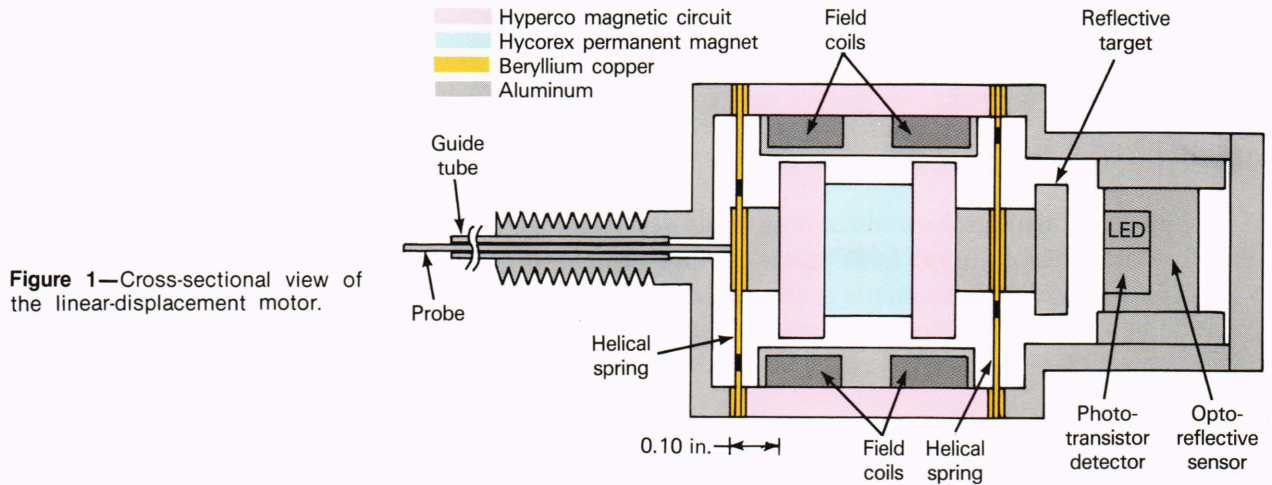
cobalt alloy. Measured motor parameters for this design are as follows:

Coil resistance	51 Ω
Moving mass	7 g
Spring constant	0.42 N/mm
Force constant	2.65 N/A

Position sensing is achieved by an optoreflective sensor encased in a light-tight, light-absorptive housing, mounted on the rear of the motor. The sensor consists of an infrared light-emitting diode (LED) housed adjacent to a phototransistor detector in a 5-mm-diameter cylindrical package. Light from the LED is directed at a 6.5-mm-diameter diffusely reflective target attached to the rear end of the motor shaft. The motion of the target will modulate the amount of LED light reflected to the detector nonlinearly, resulting in the detector current/distance relationship shown in Fig. 2. The most linear portion of the trailing part of the curve is chosen as the region of operation for the sensor. The detector bandwidth is a function of the detector's load resistance. The LED current, for a given detector load resistance, is adjusted to position the region of operation of the sensor around the desired operating point. Increasing the LED current will tend to increase the dynamic range of the sensor, but at the expense of thermal stability. The sensor has been trimmed for a 1000-Hz bandwidth and a 2-μm noise level in a 1-mm range.

The motor's motion is transferred to the experimental surface of the skin via a 10-cm-long, 0.5-mm-diameter stainless steel syringe tube attached to the front end of the motor shaft. The long tube is necessary in order to concentrate the motions from the larger motor array into the closeness required at the experimental surface. The tube is encased in a 0.9-mm-diameter syringe tube soldered to the front cap of the motor. The purpose of the outer tube is to protect the inner tube and prevent it from buckling under reactive forces from the skin that occur at the tip of the inner tube.

Two problems are created by this method of transferring motion from the motor to the skin: first, the tubes will touch each other either from slight inherent curva-
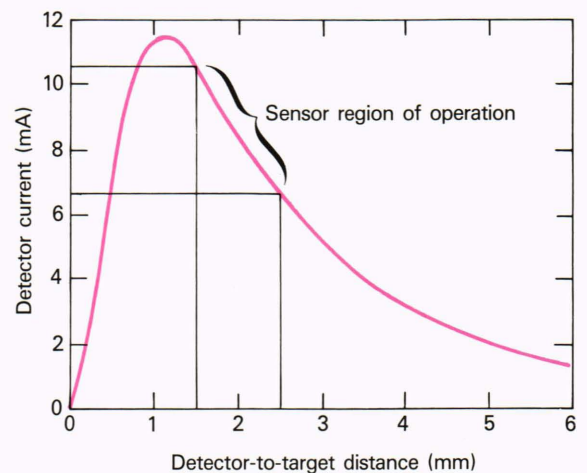

Figure 2—Static transfer characteristics of the optoreflective sensor.

tures or from the buckling of the inner tube when it is under a reactive load; second, the touching causes various levels of friction and stiction between the tubes, degrading the motor performance at micrometer levels of motion. The buckling compliance of the inner tube will further tend to attenuate the motion at the tip of the tube relative to that applied by the motor at the base. The breakaway force needed to impart relative motion between the tubes (stiction) will combine with the compliance of the inner tube to prevent motion transfer at micrometer levels.

THE TACTILE ARRAY ASSEMBLY

The tactile array assembly is shown in Fig. 3. It has 13 linear motors, each of which is screwed into a threaded nylon ball. The balls, which are clamped between two slightly flexible mounting plates that have spherical surface holes milled in them, allow the motors to pivot in the mounting holes for fine radial adjustments of the probe tips. Gross axial length adjustments are made by screwing the motors into or out of the balls. The mounting plates can be rotated relative to the mount so that
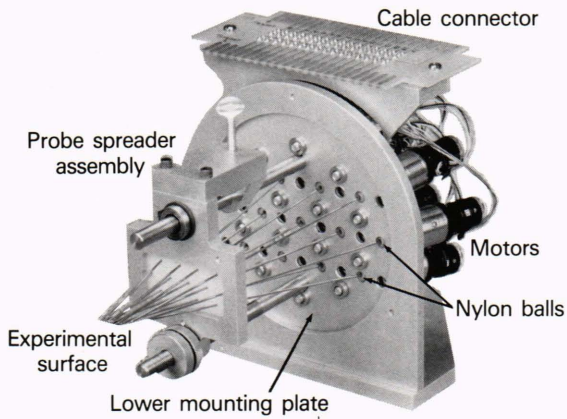
Figure 3—Tactile stimulator array assembly.

the array can be positioned with various orientations on the experimental surface.

One of the requirements of the small linear 13 by 1 array was that its interprobe spacing could be varied from 0.6 to 2.0 mm for receptor field studies, a variation achieved with the help of an adjustable nylon spreader mechanism. Since it is impossible to map a three-row arrangement of motors into a linear array at the probe tips for a variably positioned spreader plate, other adjustments are necessary. Fine adjustments to the tip positions of the radial probe must be made by using the spreader plate as a pivot point for the guide tube while the motor is pivoted in its ball socket by moving the back end of the motor radially.

THE ARRAY CONTROLLER

The array controller consists of a microprocessor-based array control computer (ACC) and a servo channel for each motor of the array (Fig. 4).

The main task of the ACC is to command all servo channels with precomputed commands to simulate either stationary or moving three-dimensional surfaces for a rectangular array. Ideal surfaces are, of course, only approximated by the motion of the individual motor-driven probes. Precomputed commands for complex surfaces can be generated on an experiment-control computer and downloaded to the ACC. Simple surfaces can be generated by the ACC's motor-command-file editor.

A command-generation system should be able to generate commands with a greater resolution than that of the servo being commanded. Also, the commands should be generated in a manner that does not introduce extraneous noise within the bandwidth of the servo and that does not require an excessive data rate or storage requirement.
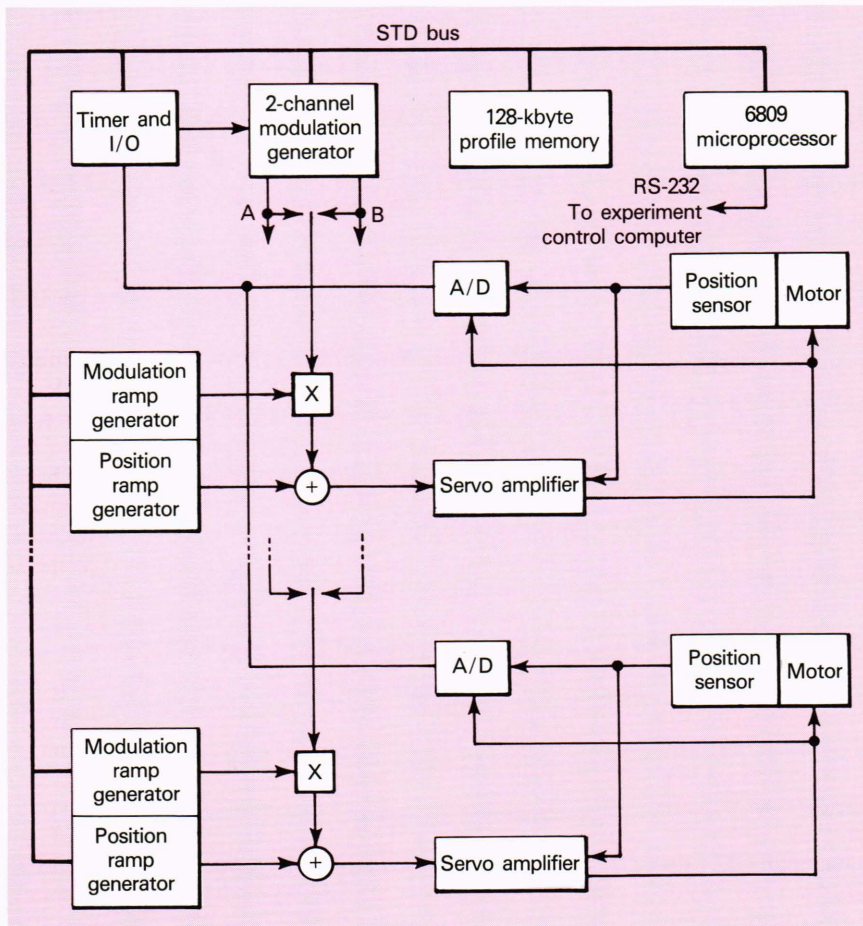

Figure 4—Block diagram of the array controller.

The conventional approach of commanding the servo directly from a digital-to-analog converter (DAC) would require a high update rate to place the converter's update noise above the upper frequency response (>500 Hz) of the Pacinian corpuscles. The DAC, acting as a zero-order hold, will quickly update its analog output when its digital input is changed and will hold that output until the next input change. The resulting step change, occurring at a periodic interval, is the source of the update noise.

Ramp generators were used to generate the motor commands because a series of slope approximations to the motor command reduces both the data rate and the storage requirements while minimizing the update steps, for motor commands having components that are of low frequency relative to the Pacinian corpuscle response.

Each ramp generator consists of two DACs, updated every 5 ms, that provide inputs to a 50-ms filter. The DAC having a unity gain into the filter will act as a zero-order hold for the position command, while the other DAC having a gain of 9.51 will act as a first-order hold for the slope command (Fig. 5). The case described will only hold, however, if the position command at sample n is the sum of the position increments achieved by slope commands for previous samples plus the slope command of sample n. The slope command adds to this sample the time integral of its value for one interval. The parameter relationships of the ramp generator as shown in Fig. 5 must exist for proper operation of this scheme.

The position commands to each motor servo (Fig. 4) are of the form

$$PRG + MRG \times modulation,$$

where PRG is the output of the unmodulated position ramp generator that can be used to bias the probe position. The product of MRG (modulation ramp generator) output and a modulation waveform is the modulated position command that will move the probe around the biased position supplied by the PRG.

Figure 6 shows a command sequence from a modulation ramp generator to produce a short burst of sine waves for a motor command. It can be seen that the position commands to the ramp generator at sample n are the sums of the position increments achieved by the slope commands up to sample $n + 1$. The resultant modulation ramp is then multiplied by the 250-Hz sine-wave modulation to produce the modulated motor command. This command sequence required only 16 bytes to specify the burst of sine waves. Using this approach to command generation requires, at most, 800 bytes per second per motor.

The ACC is based on a 6809 processor executing the Forth language. Forth is an interpretive language that allows its vocabulary to be extended. The extension feature enables the use of names for words (functions, variables, constants, and commands), names that are meaningful to the investigator. Words may be renamed or defined to suit the needs of the investigator. New words are incrementally compiled and are thus immediately
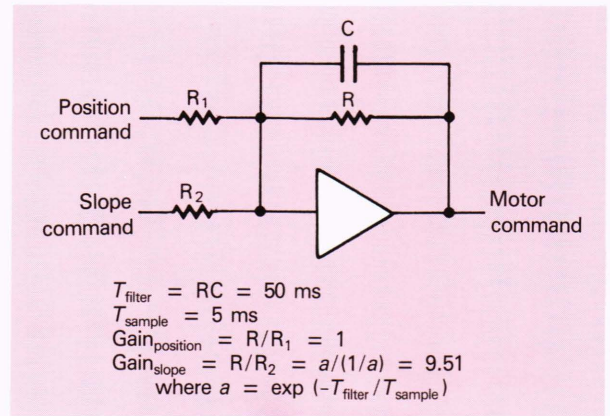

$T_{filter} = RC = 50$ ms
$T_{sample} = 5$ ms
$Gain_{position} = R/R_1 = 1$
$Gain_{slope} = R/R_2 = a/(1/a) = 9.51$
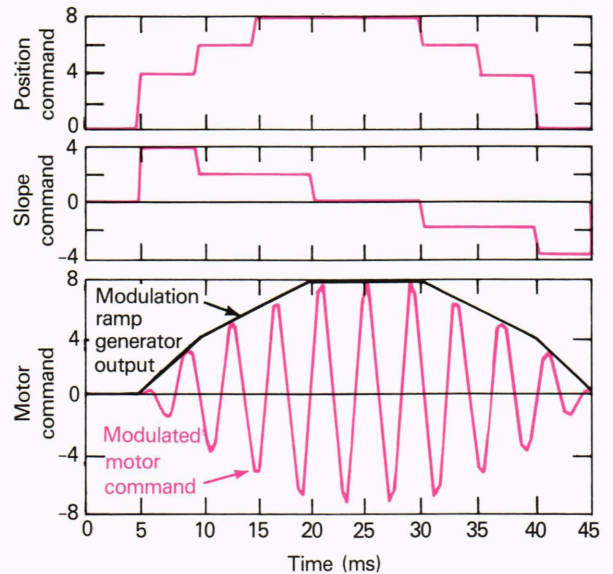where $a = \exp(-T_{filter}/T_{sample})$

Figure 5—Ramp generator.

Figure 6—An example of motor command generation.

available for use. Nonvolatile solid-state memory is used to store new definitions.

All ACC and servo cards are designed to work on an STD bus. The four servo channels packaged to one card include an eight-channel analog-to-digital converter that can be used to monitor the motor performance for calibration and maintenance. Each of the two modulation generators can be programmed to generate any 256-point waveform that can be played at a rate ranging from 1 to 500 Hz. Square waves and triangular waves can be used to command the motor for performance monitoring. In-phase or out-of-phase sine waves of various frequencies would be used for experimental modulations. Each motor channel can be wired to the modulation channel of choice.

FUTURE ARRAYS

Although use of the current array is just beginning, tactility researchers are already interested in arrays having dimensions greater than 12 by 12. Experience with

the described approach to multipoint tactile stimulation has shown that the fabrication of large arrays will face many problems, only one of which is cost. Further integration of the servo electronics for closer placement to the motors will be necessary to reduce the cabling and to increase reliability. Pulsewidth-modulated motor-drive stages, with their higher efficiency, may be needed to reduce the electronics cooling requirements for the more integrated electronics. The most difficult problem remaining is to produce hundreds of the smaller precision motors at reasonable cost.
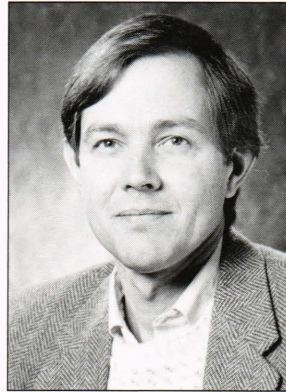
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[2] Workshop on Tactile Stimulators, Indiana University, May 9, 1985 (personal notes).
[3] J. G. Chubbuck, "Small Motion Biological Stimulator," *Johns Hopkins APL Tech. Dig.* **5**, 18–23 (1966).

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