INSTRUMENTATION & TECHNIQUES

Instrumentation for an electrocutaneous communication device

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The device described is a prototype that uses spatiotemporal resolution for electrocutaneous stimulation. Signals initiated through a keyboard activate a matrix of four electrodes that may be applied to the fingers, forearm, abdomen, back, or other parts of the integument. The instrumentation described includes a pulse generator, the active time and delay time controls, the control of the total length of a pulse train, and the constant-current generators whose output is fed into the electrodes. This device may be used as an interface with an alphanumeric device (e.g., a calculator or computer) and as a basic instrument in research investigating the spatial and temporal resolving capacities of the skin senses.

The device described in this article is a prototype of an electrocutaneous stimulator capable of presenting stimulus pulses of varying duration at different inter-stimulus delays to any combination of four electrodes using a braille-like code. This matrix of electrodes may be applied to the fingers, forearm, abdomen, back, or other parts of the integument. Since spatial resolution alone may be difficult or impossible to achieve at certain bodily locations, this instrument has been designed to add a temporal dimension to the resolution. Specifically, the stimulus duration for each electrode may be varied from 50 msec to 10,000 msec, with delay between successive stimuli varying from 50 msec to 50,000 msec.

Use of the skin senses as a mode by which information may be presented to a person has a long history (see Geldard, 1961, 1970). Recently, much basic and applied research has led to the development of devices that use the skin senses as a substitute for encoding information usually presented through the visual (e.g., Bach-y-Rita, 1972; Craig, 1974; Geldard, 1966; Linvill & Bliss, 1966; Melen & Meindl, 1971) or auditory (Goldstein, Stark, Yeni-Komshian, & Grant, 1976; Saunders, 1974) systems.

Two types of stimulation have been used in these studies: vibrotactile, in which vibrating mechanical stim-

ulation is applied to the skin, and electrical, in which either a single pulse or trains of pulses are applied to the skin. Both methods have been in basic research and in the development of sensory aids.

Representative research involving investigations of the quantitative, qualitative, spatial, and temporal parameters of stimulation using these two modes of stimulation is presented in Table 1.

In addition, these modes of stimulation have been incorporated into several devices designed as sensory aids for the visually and auditorily impaired, such as the Optacon (Linvill & Bliss, 1966), TVSS (White, Saunders, Scadden, Bach-y-Rita, & Collins, 1970), and the Vocoder (Saunders, Note 1; Yeni-Komshian & Goldstein, 1977).

The present device provides an electrical mode of stimulation; it has several features similar to those reported by Prior (1972) and by Saunders (1974) and others that are unique. This device is a prototype of one that may be used as an interface with an alphanumeric device (e.g., a calculator or computer) and as a basic instrument in research investigating the spatial and temporal resolving capacities of the skin senses.

OVERALL DESIGN OF INSTRUMENT

As shown in the block diagram in Figure 1, the four electrodes are controlled by four constant-current (CC) generators. These CC generators are activated by the pulse generator and the keyboard. The signal from the pulse generator is applied continuously, and the signals from the keyboard determine which electrodes will be

An appendix to this paper has been prepared that contains detailed wiring diagrams and explicit tabulations of pin connections of all integrated circuits, EPROMs, and so on. This appendix may be obtained by applying to Brother Gabriel Kane, FSC, PhD, Physics Department, Manhattan College, Bronx, New York 10471.

Table 1
Representative Research on the Quantitative, Qualitative, Spatial, and Temporal Parameters
of Vibrotactile and Electrocutaneous Stimulation

Quantitative	Qualitative	Spatial	Temporal
Vibrotactile			
Craig, 1966 Verrillo, 1974 Verrillo, Fraioli, & Smith, 1969	Goff, 1967 Frisina & Gescheider, 1977	Craig, 1968 Craig & Sherrick, 1969 Gottheil, Cholewiak, & Sherrick, 1978	Berglund, Berglund, & Ekman, 1967 Sherrick, 1970 Geldard & Sherrick, 1972
Electrocutaneous			
Hawkes, 1961 Tursky & Watson, 1964 McCallum & Goldberg, 1975 Rollman, 1974 Babkoff, 1976	Gibson, 1968 Tashiro & Higashiyama, 1981	Matin, 1959 Melen & Meindl, 1971	Schmid, 1961 Rosner, 1964 Babkoff, 1978

Figure 1. Block diagram of the entire circuit.

active at any time. Intermediate between the keyboard and the CC generators are the input and output monitors and the active and delay time controls.

PULSE GENERATOR

The pulse generator used is similar to but not identical to the "haptode" or "quantal stimulator" described by Saunders (1974). In his device, the basic stimulus consisted of a quantal cycle (QC), defined as a positive pulse followed 25 microsec later by a negative pulse, which in turn was followed by 50 microsec off time, for a total cycle time of 100 microsec. The positive and negative pulses were adjusted from 0 to 20 microsec, thus introducing a small delay between them. The pulse repetition rate for QCs was 10,000 pulses/sec. The stimuli were then gated in bursts at a burst repetition rate (BRR) of 250 Hz. Each burst contained from 0 to 40 quantal stimuli, thereby providing a means by which intensity could be modulated.

In the present design, the QC consists of a positive pulse, followed by an off time, followed by a negative pulse, followed by another off time. The pulse widths are adjustable from 0 to 50 microsec, and the period

of the QC is fixed at 312.5 microsec. The pulses are formed into "bursts," each burst consisting of 16 QCs as described above ($312.5 \text{ microsec} \times 16 = 5,000 \text{ microsec}$), followed by a similar period (5,000 microsec) of "off" time. The resulting burst lasts 10,000 microsec (10 msec), as shown in the lower part of Figure 2. Bursts can be repeated if desired at a BRR of 100 Hz (1 burst/10 msec). This rate results in a tingling or vibrating sensation to the skin (Prior Note 2).

The pulse generator (shown schematically in Figure 3) contains the following integrated circuits (ICs): 555 timer, 4047 monostable/astable multivibrator, 4024 seven-stage binary ripple counter, 4082 dual four-input AND gate, and two 4050 hex noninverting buffers and TTL drivers. IC 555 serves as a timer or clock. It provides a frequency (adjustable over a short range) that has a period equal to one-half the period of a quantal pulse, or 156.25 microsec.

Two outputs are used from the binary counter IC 4024. The Pin 12 output ($\div 2^1$) has a period of $156.25 \text{ microsec} \times 2 = 312.5 \text{ microsec}$ and provides for the alternation of positive and negative pulses. The Pin 4 output ($\div 2^6$) has a period of $156.25 \text{ microsec} \times 64 = 10 \text{ msec}$. It provides for the gating on and off of the pulses every 16th pulse pair, thereby providing the 16 QCs "on" and the 16 QCs "off" that make up a single burst. These outputs are combined with pulse output of IC 4047 in IC 4082, resulting in outputs at Pins 1 and 13, as shown in the upper parts of Figure 2. These two signals are buffered by IC 4050A and IC 4050B and are then fed to the positive and negative pulse input connections of the four CC generators. The CC generators' circuits will be described later.

Keyboard

As mentioned above, the CC generators are activated by signals originating from the pulse generator and the keyboard.

A 19-key hexadecimal keyboard is used. Of these 19 keys, only the 0-9 and the A-F are actually used.

Figure 2. Formation of constant-current stimulus waveform.

Figure 3. Pulse generator circuit.

INPUT AND OUTPUT MONITORS

The keyboard controls for the CC generators are monitored at the input by a seven-segment light-emitting diode (LED) and at the output by four single LEDs arranged in a braille-like pattern. Figure 4 shows the responses of the seven-segment LED and the four single LEDs as each of the keyboard characters is depressed.

Two erasable programmable read-only memories (EPROMs) are used to monitor the input from the hexadecimal keyboard. The output from the keys 0-7 are fed to EPROM 1 and the output from the keys 8, 9, and A-F are fed to EPROM 2. A TTL 7448 BCD to seven-

segment decoder feeds directly into the seven-segment LED. The four single LEDs are connected to the output of a TTL 7407 hex buffer.

CONSTANT-CURRENT GENERATORS

The design of the CC generators used in this instrument was adapted from Saunders (Note 1, Note 3) and described by him as a "haptode current driver." The "haptode" current driver is essentially a high-voltage operational amplifier ac capacitively coupled to a stimulating electrode. The high-voltage operational amplifier contains five high-voltage transistors. T1 and T2 perform

Keyboard characters depressed															
0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
Seven segmented LED's responses															
0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
Four single LEDs' responses															
0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F

Figure 4. Response to keyboard of input and output monitors.

as a current mirror (Heinlein & Holmes, 1974; Widlar, 1965). Positive and negative pulses are fed into the bases of T3 and T4. The base of T5 is gated from an output of IC 7406 to permit the current to be turned on and off. There are four CC generators, each one being used to activate one of the four electrodes.

Electrodes

Concentric electrodes made of silver are used; each has an active center, an insulating ring, and a surrounding ground. These are similar to those used by Prior (1972).

Dummy Loads

Toggle switches are used to provide a choice between dummy loads and human subjects being stimulated by electrodes.

Monitors

By means of these toggle switches, 100-ohm resistors are placed between ground and either the dummy loads or the electrodes. The voltage across these resistors may be monitored with an oscilloscope, thereby determining the current that is flowing through the dummy loads or the electrodes.

ACTIVE AND DELAY TIME CONTROLS

Temporal resolution is achieved by means of the active and delay time controls. These constitute a network of approximately a dozen integrated circuits. One portion of this network initiates the determination of the active time for stimulation plus the delay time between stimuli while another portion of the network initiates the determination of the delay time between stimuli, so that the actual active stimulation time becomes the difference between these two parameters. The active plus delay time is adjustable from 100 msec to 10,000 msec, and the delay time is adjustable from 50 msec to 5,000 msec.

The overall circuit gates the quantal bursts sequentially from the pulse generator to the four CC generators, causing only a single electrode to be gated "on" at any particular time. Considering the case of four-finger stimulation, each finger would receive active stimulation for equal times and equal delay times between stimuli. The sequence in this case would be 1, 2, 3, 4, 1, 2, 3, 4, and so on. If, however, three fingers or fewer are to be stimulated, the circuit is designed so as not to permit a "dead time" for the finger or fingers not to be stimulated. For instance, if only Fingers 1, 2, and 4 were to be stimulated, the sequence would be 1, 2, 4, 1, 2, 4, and so on.

TOTAL LENGTH OF PULSE TRAINS

The instrument described thus far operated in a continuous mode, the duration of the stimuli being determined manually by the length of time that the fingers are held on the keyboard. Since it is useful for certain experimental purposes, a time control mode has been introduced in addition to the continuous mode. The time control range varies from 2 sec to 20 sec.

REFERENCE NOTES

1. Saunders, F. A. *Research with a wearable electrotactile vocoder*. Paper presented at the Research Conference on Speech-Processing Aids for the Deaf, Gallaudet College, Washington, D.C., May 1977.
2. Prior, R. Personal communication, 1976.
3. Saunders, F. A. Personal communication, 1977.

REFERENCES

- BABKOFF, H. Magnitude estimation of short electrocutaneous pulses. *Psychological Research*, 1976, 39, 39-49.
- BABKOFF, H. Electrocutaneous psychophysical input-output functions and temporal integration. *Perception & Psychophysics*, 1978, 23, 251-257.
- BACH-Y-RITA, P. *Brain mechanisms in sensory substitution*. New York: Academic Press, 1972.

- BERGLUND, B., BERGLUND, U., & EKMAN, G. Temporal integration of vibrotactile stimulation. *Perceptual and Motor Skills*, 1967, 25, 549-560.
- CRAIG, J. C. Vibrotactile loudness addition. *Perception & Psychophysics*, 1966, 1, 185-190.
- CRAIG, J. C. Vibrotactile spatial summation. *Perception & Psychophysics*, 1968, 4, 351-354.
- CRAIG, J. C. Pictorial and abstract cutaneous displays. In F. A. Geldard (Ed.), *Conference on vibrotactile communication*. Austin, Tex: Psychonomic Society, 1974.
- CRAIG, J. C., & SHERRICK, C. E. The role of skin coupling in the determination of vibrotactile spatial summation. *Perception & Psychophysics*, 1969, 6, 97-101.
- FRISINA, R. D., & GESCHIEDER, G. A. Comparison of child and adult vibrotactile thresholds as a function of frequency and duration. *Perception & Psychophysics*, 1977, 22, 100-103.
- GELDARD, F. A. Cutaneous channels of communication. In W. A. Rosenblith (Ed.), *Sensory communication*. New York: Wiley, 1961.
- GELDARD, F. A. Cutaneous coding of optical signals: The optohapt. *Perception & Psychophysics*, 1966, 1, 377-381.
- GELDARD, F. A. Vision, audition, and beyond. In W. A. Neff (Ed.), *Contributions to sensory physiology* (Vol. 4). New York: Academic Press, 1970.
- GELDARD, F. A., & SHERRICK, C. E. The cutaneous "rabbit": A perceptual illusion. *Science*, 1972, 178, 178-179.
- GIBSON, R. H. Electrical stimulation of pain and touch. In D. Kenshalo (Ed.), *The skin senses*. Springfield, Ill: Thomas, 1968.
- GOFF, G. D. Differential discrimination of frequency of cutaneous mechanical vibration. *Journal of Experimental Psychology*, 1967, 74, 294-299.
- GOLDSTEIN, M. H., STARK, R. E., YENI-KOMSHIAN, G., & GRANT, D. G. Tactile stimulation as an aid for the deaf in production and reception of speech: Preliminary studies. *Conference Record, I.E.E.E. International Conference on Acoustics, Speech, and Signal Processing*, 1976, pp. 598-601.
- GOTTHEIL, E. F., CHOLEWIAK, R. W., & SHERRICK, C. E. The discrimination of vibrating patterns on a tactile matrix. *Bulletin of the Psychonomic Society*, 1978, 11, 21-24.
- HAWKES, G. R. Cutaneous discrimination of electrical intensity. *American Journal of Psychology*, 1961, 74, 45-53.
- HEINLEIN, W. E., & HOLMES, W. H. *Active filters for integrated circuits*. New York: Springer-Verlag, 1974.
- LINVILL, J. G., & BLISS, J. C. A direct translation reading aid for the blind. *Proceedings of the IEEE*, 1966, 54, 40-51.
- MATIN, E. *Temporal aspects of cutaneous interaction with two-point electrical stimulation*. Unpublished doctoral dissertation, Columbia University, 1959.
- MCCALLUM, P., & GOLDBERG, H. Magnitude scales for electrocutaneous stimulation. *Perception & Psychophysics*, 1975, 17, 75-78.
- MELEN, R. C., & MEINDL, J. D. Electrocutaneous stimulation in a reading aid for the blind. *IEEE Transactions on Bio-Medical Engineering*, 1971, BME-18, 1-3.
- PRIOR, R. *Study of electrocutaneous parameters relevant to dynamic tactual communication systems*. Unpublished doctoral dissertation, University of California at Los Angeles, 1972.
- ROLLMAN, G. Electrocutaneous stimulation. In F. A. Geldard (Ed.), *Conference on vibrotactile communication*. Austin, Tex: Psychonomic Society, 1974.
- ROSNER, B. S. Temporal interaction between electrocutaneous stimuli. *Journal of Experimental Psychology*, 1964, 67, 191-192.
- SAUNDERS, F. A. Electrocutaneous displays. In F. A. Geldard (Ed.), *Conference on communication systems and devices*. Austin, Tex: Psychonomic Society, 1974.
- SCHMID, E. Temporal aspects of cutaneous interaction with two-point electrical stimulation. *Journal of Experimental Psychology*, 1961, 61, 400-409.
- SHERRICK, C. E. Temporal ordering of events in haptic space. *IEEE Transactions on Man-Machine Systems*, 1970, 11, 25-28.
- TASHIRO, T., & HIGASHIYAMA, A. The perceptual properties of electrocutaneous stimulation: Sensory quality, subjective intensity, and intensity-duration relation. *Perception & Psychophysics*, 1981, 30, 579-586.
- TURSKY, B., & WATSON, P. D. Controlled physical and subjective intensities of electric shock. *Psychophysiology*, 1964, 1, 151-162.
- VERRILLO, R. T. Vibrotactile intensity scaling at several body sites. In F. A. Geldard (Ed.), *Conference on vibrotactile communication*. Austin, Tex: Psychonomic Society, 1974.
- VERRILLO, R. T., FRAIOLI, A. J., & SMITH, R. L. Sensation magnitude of vibrotactile stimuli. *Perception & Psychophysics*, 1969, 6, 366-372.
- WHITE, B. W., SAUNDERS, F. A., SCADDEN, L., BACH-Y-RITA, P., & COLLINS, C. C. Seeing with the skin. *Perception & Psychophysics*, 1970, 7, 23-27.
- WIDLAR, R. J. Some circuit design techniques for linear integrated circuits. *IEEE Transactions on Circuit Theory*, 1965, 12, 586-590.
- YENI-KOMSHIAN, G., & GOLDSTEIN, M. H., JR. Identification of speech sounds displayed on a vibrotactile vocoder. *Journal of the Acoustical Society of America*, 1977, 62, 194-198.

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