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A TACTILE PAGING SYSTEM FOR DEAF-BLIND PEOPLE
PHASE I

By:

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February 1976

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SUMMARY

A tactile paging system for deaf-blind people has been brought from the concept stage to the development of a first model. This model consists of a central station that transmits coded information via radio link to an on-body receiving unit, the output from which is a coded vibrotactile signal.

The purpose of the system is to facilitate communication to deaf-blind clients in an institutional environment and aid in their training and other activities. The purpose of the project was to provide an initial demonstration of the feasibility of such a system, to define and refine operating characteristics, and to provide a vehicle for evaluating the system concept and device design details. The several subunits of the system have been individually developed, tested, and integrated into an operating system ready for experimentation and evaluation.

ACKNOWLEDGMENT

The author is responsible for this report; however, contributions have been made by others, and the project accomplishments accrue from the diligent and cooperative effort of many individuals. John M. Yarborough was responsible for the design of the code structure and the control logic. C. Bruce Clark, assisted by Thomas J. Drewek and Nickolas P. Krea, was largely responsible for the alert stimulator development and contributed to other aspects of the work. Russell T. Wolfram and James C. Gaddie were responsible for the radio frequency portions of the system. John P. Gill contributed to the development of the message stimulator.

In addition to the above SRI personnel, the active participation of Frederick M. Kruger, National Center for Deaf-Blind Youths and Adults, and James L. Jones, NASA Ames Research Center, has contributed significantly to the success of this project.

I INTRODUCTION

The tactile paging system described in this report is based on a concept developed by Dr. Frederick M. Kruger, Director of Research for the National Center for Deaf-Blind Youths and Adults located at Sands Point (Long Island), New York. This project was funded by NASA through its Office of Technology Utilization, and the work is based in part on SRI's earlier tactile perception studies under NASA contract. A first model of the system has been developed and delivered to the National Center for evaluation. It is anticipated that additional models will be developed in the future to enhance performance and to add new features.

The paging system is intended to provide a means for communicating with deaf-blind people in an institutional environment (specifically the National Center; Dr. Kruger is developing another type of communication system for use in a residential environment). During training and rehabilitation of clients at the Center, communication with selected groups and selected individuals is required on a routine basis and during emergency conditions. For example, a signal is needed during classroom training sessions to denote break periods and to define the beginning and end of sessions. In the event of a fire alarm, all clients must be quickly alerted to danger, and routine messages--such as notification of an individual that a visitor has arrived--require a means of communication. Plans call for a final system that will allow 100 clients of the National Center to use the system at the same time, and installation of additional systems at other locations is anticipated for the future.

Communication using the tactile sense can be effective for a person who is both deaf and blind. In this experimental system, the modality is time-sequential tactile signals, transmitted to either the user's wrist or finger. The signals are generated in an on-body unit that responds to coded radio transmission signals originating at a central control and transmitting station. The system is similar in this respect to commercially available radio paging system of the sort commonly used by physicians.

This tactile paging system is referred to as the "Wrist-Com" by Dr. Kruger; the name signifies communication by means of a wrist-worn receiving unit. In the present implementation, the battery-powered on-body portion of the system consists of two modules; a tactile stimulator assembly, worn on the wrist, and a camera-size electronic module, carried on a shoulder strap. One goal for future work is to miniaturize the on-body portion so it can be packaged in a single wrist-worn unit. Another goal is to expand the present simplex (one-way) communication channel to duplex (two-way) communication, thereby permitting the client to acknowledge receipt of a message and request aid in the event of an emergency.

The present Wrist-Com model operates at a frequency of 170.4 MHz; this government frequency assignment was obtained by NASA for system development purposes. Ultimately, the National Center will need to obtain a frequency assignment from the FCC for operational use.

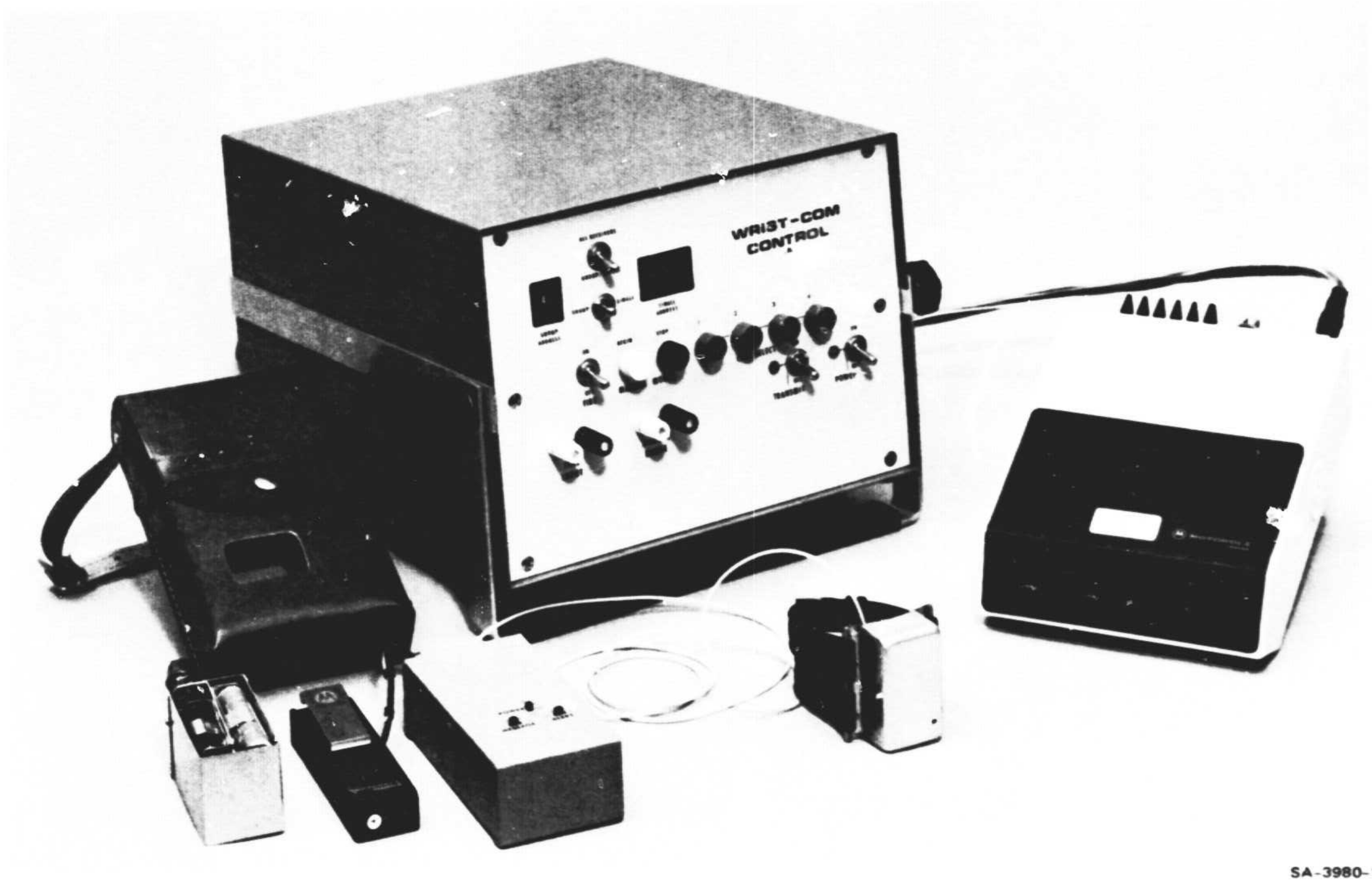
The hardware that has been delivered to the National Center is the principal product of this project. Uniqueness of the project lies primarily in the specialized application of technology; development of new techniques is of secondary importance. The following sections of this report describe the operation and characteristics of the tactile paging system and the basis for its implementation.

II CHARACTERISTICS OF THE FIRST MODEL

A. General

The first model of this tactile paging system as delivered to the National Center for testing and evaluation is pictured in Figures 1 and 2. Figure 1 shows the central station equipment (except for the antenna) in the background part of the photograph, and shows the on-body module components grouped in the foreground. The central station consists of a 10-watt commercial transmitter (Motorola Model L33TRB1100AM) and an SRI-designed control unit (labeled "Wrist-Com Control" on the front panel).

The wrist-worn stimulator assembly in the center foreground of Figure 1 is connected by a small cable to the electronics module. The stimulator assembly, which measures approximately 40 × 60 × 25 mm, is fastened to the wrist by two straps. The electronics module consists of three separate packages contained in a leather case. The leftmost package, in front of the case in Figure 1, is a battery pack; a commercial Motorola Pageboy II receiver is shown in the center, and the SRI-designed demodulator and control logic are in the box on the right. These three units will ultimately be miniaturized, as will the stimulator assembly, to reduce the size and weight of the on-body part of the system. Figure 2 shows the on-body modules as they will be worn by clients at the National Center to obtain performance data. The index finger of the right hand in this demonstration is in contact with one of the stimulators and is ready to receive tactile information.



SA-3980-1

FIGURE 1 FIRST MODEL OF TACTILE PAGING SYSTEM

SA-3980-2

FIGURE 2 SIMULATED USE OF TACTILE PAGING SYSTEM

B. Stimulator Assembly

The stimulator assembly consists of an alert stimulator, a message stimulator, a pushbutton switch, and an electrical noise filter, all housed in a sealed container. In principle, the alert stimulator is the only tactile transducer required by this system. However, the power required to operate the alert stimulator--about 400 milliwatts (mW) in this model--is too high to achieve a reasonable battery life. Principally because of the power level required by this stimulator, a dual stimulation method has been developed. The (relatively) high-power alert stimulator is used for some functions; a lower-power "message stimulator" is used for other functions. The low duty cycle used in the alert stimulator--partly because of the dual stimulator implementation--reduces the average power required to operate the alert stimulator to the 2- to 5-mW region.

The alert stimulator transmits three different codes to the user, representing "Fire Alarm," "Message Available" (indicating that coded information is present at the message stimulator), and a "Time Period Indication." The Time Period Indication will be used hourly at the National Center at the 50th and 60th minutes of the hour to signal the beginning and end of classroom and training sessions, and break periods.

The alert stimulator is turned on automatically by the on-body electronics in response to the central transmitter and control station, and no action is required by the recipient of the message, other than interpreting it. A tactile sensation is caused by a rapid shaking motion of the entire stimulator assembly on the wrist of the wearer. A time-sequential code is transmitted by the alert stimulator being turned on and off at appropriate time intervals. For example, the code for Fire Alarm consists of a repeated cycle of shaking motion of 1/2 second, followed by no motion for 1-1/2 seconds. A pushbutton switch permits the user to terminate the

Time Period Indication and Message Available signals; however, the switch will not terminate the Fire Alarm signal. The Fire Alarm signal can be terminated only by the central control station.

The shaking motion of the alert stimulator is caused by a small dc electric motor (Escap No. 16C11-210-1, made by Portescap in Switzerland), which has an eccentric mass attached to its rotating shaft. The intensity of stimulation is controlled by varying the value of the resistance in series with the motor--high- and low-intensity switch positions can be selected by the user. Other means of implementing the alert stimulator were considered as a part of this project; these are discussed in Section III.

In contrast to the alert stimulator operation, the message stimulator requires specific action by the user before a message can be communicated to the user, namely, a finger is placed on a vibrating metal pin--see Figure 2. Because the message stimulator requires this specific action, the use of this low-power stimulator without an alert stimulator is not an acceptable implementation.

The sequence of operation is as follows:

(1) A Message Available signal is presented to the user by the coded shaking motion of the wrist-mounted assembly.

(2) Upon recognition of the coded signal, the user depresses the pushbutton switch to terminate the alert stimulator activation (this is an optional action by the user to avoid the annoyance of unnecessary stimulator motion and also saves battery power--after the coded character has been repeated several times the stimulator is automatically turned off by the on-body electronic logic if the user does not terminate it).

(3) The user places a finger over the vibrating pin to receive a time-sequential coded character.

Two types of messages are presented by the message stimulator; the first type consists of a single Morse-code character that is repeated several times. Four such characters can be presented; the meaning of each character will be assigned by the Center as needs dictate. The second type of message is a string of Morse-code characters, sent by the central station operator under manual control. In this mode of operation, the time-sequential modulation of the radio transmitter is identical to the time-sequential vibrotactile signal presented by the message stimulator. This direct time-sequential correlation is not true for other coded characters, as will be explained subsequently.

The message stimulator consists of a cantilevered piezoelectric reed vibrating in the flexure mode. The reed is a layered (sandwich) structure of two thin pieces of piezoelectric ceramic material, each of which is bonded to a brass "vane." The brass is in the center of the layered structure, and together with deposited metal on the ceramic faces it forms one electrode of the device (the primary purpose of the brass vane is to strengthen the sandwich mechanically). Metal deposited on the remaining top and bottom surfaces of the ceramic pieces forms two more electrodes. This layered device is called a Bimorph by the manufacturer (Vernitron Piezoelectric Division). The electroded piezoelectric ceramic material is designated PZT-5HN. The practicality of using this vibrating reed as a vibrotactile stimulation method has been established by the commercial development of the Optacon, a reading aid for blind people that was developed by Stanford University and SRI.[1] In the Optacon, 144

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[1] J. A. Baer and J. W. Hill, "Optical-to-Tactile Image Conversion for the Blind," Contract SRS 70-42 and Grant 14-P-55296/9-02, SRI Projects 8647 and 1417, Stanford Research Institute, Menlo Park, California (June 1972).

vitrating reeds present a time-dependent spatial image to the user's finger. The message stimulator uses only a single vibrating reed, and the information is carried in the time-sequential coding of the vibration. The Bimorph implementation of the message stimulator allows for the possibility of enhancing the information transfer in later models of the Wrist-Com to include the spatial modality. Specifically, a six-point Braille cell geometry could be implemented, should this become a requirement. This possibility is another reason for the dual stimulator implementation in the Wrist-Com, although power saving remains the primary reason.

The piezoelectric vibrator in the message stimulator provides a more intense stimulation than does a single vibrator in the Optacon. Some information redundancy inherent in the Optacon operation is not present in the Wrist-Com, and this is one reason for the difference in the required intensity. Additionally, the increased intensity (a factor of about 5) in the message stimulator is intended to make communication feasible with minimal training, even for clients who do not have well-developed tactile sensitivity.

The vibration frequency of the Bimorph is 150 Hz--chosen because the finger has good tactile sensitivity in this frequency region. Morse code is represented by long and short periods of vibration for a dash and dot, respectively. The power required to drive Bimorph at 150 Hz is about 6 mW. However, because of the low duty cycle of use, the average power is expected to be a few hundredths of a milliwatt. At full intensity the Bimorph requires a 45-V low-power source to drive it; in this first model the power is provided by series-connected 30-V and 15-V batteries. A switch is available for the user to change from 45 V to 30 V for the Bimorph charging source; this provides high- and low-intensity stimulation for experimental purposes. Later models will use a dc-to-dc converter driven by a 5.4-V battery as the power source.

The codes that are available from the message and alert stimulator are the following:

- Alert Stimulator
  - Fire Alarm--ON for one unit of time, OFF for three units of time; repeat.
  - Time Period Indication--ON without interruption for a specified period of time.
  - Message Available--ON for one unit of time, OFF for one unit, ON for one unit, OFF for five units; repeat.
- Message Stimulator
  - Message No. 1--dash, dash, dash.
  - Message No. 2--dot, dash, dot, dash.
  - Message No. 3--dash, dot, dash.
  - Message No. 4--dash, dot, dot, dash.

An electrical noise filter in series with the alert stimulator motor windings is included in the stimulator assembly as a precautionary measure. As the brushes and commutator wear with use, the noise generated might interfere with the radio receiver reception. Experience will indicate whether the filter will be required in subsequent models.

C. On-Body Electronics

The on-body electronics can be separated into three functional parts: RF circuits, tone demodulator, and control logic. The RF circuitry in this model is a portion of a commerically available paging receiver made by Motorola. All of the receiver package was retained in this model, although only about one-third of the internal volume is actually used. Audio tone outputs (1650 and 1178 Hz) from the receiver are fed into a phase-locked-loop FSK (frequency-shift-keyed) demodulator designed by SRI. The demodulator output is a binary voltage level that goes into the control logic. The use of CMOS integrated circuits minimizes power dissipation.

The demodulator operates from a 5.4-V battery, while the RF circuits (the Motorola receiver) operate from a 1.3-V battery. In later models the 1.3 V will be supplied by a dc-to-dc converter from the 5.4-V battery. Ultimately, a different receiver will be used at an as-yet-undetermined frequency. Evaluation of the first model may indicate that it is acceptable to reduce the receiver sensitivity and thereby simplify the receiver design requirements for later models.

The control logic input is the binary voltage derived from the demodulator, and the outputs of the logic control the alert and message stimulators. The digital code structure[2] and the control logic have been designed for reliable operation and minimum parts count. The so-called nonreturn-to-zero-inverted (NRZI) method is used to encode the binary information, and the information rate is 200 bits per second (b/s) at the input of the control logic.

The incoming bit stream has been formatted by the central station into 25-bit words. Each word contains two parts: a header and the data. The header is always a succession of eight logical ones followed by a single zero; the data word is carried in the succeeding 16 bits representing 9 bits of address code, 6 bits of message code, and 1 spare bit (set

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[2] E. N. Gilbert, "Synchronization of Binary Message," IRE Trans. on Info. Theory, Vol. IT-6, No. 4, pp. 470-477 (September 1960).

to zero). The main limitation this header places on the data codes is that no more than seven successive ones are permitted. This coding structure accommodates up to 255 on-body modules, 8 addressable groups among the 255 individuals, and an "all receivers" mode to communicate with all receivers simultaneously.

The address codes are contained in bits 7 through 15 of the data word (A_7 - A_{15}). Individual receiver addresses are in bits A_8 - A_{15} when A_7 is zero. When A_7 is a one, and A_{13} is a one, all receivers are addressed simultaneously; when A_7 is one and A_{13} is zero, group addresses are contained in bits A_9 through A_{11}.

The message codes are contained in bits 0 through 5 of the data word (M_0 - M_5). When bits M_0, M_1, and M_3 are zero (bit M_2 can be either zero or one), then bits M_4 and M_5 are interpreted as follows:

M_4	M_5	Command
0	0	Stop
0	1	Begin
1	0	Time
1	1	Fire

All other message codes are interpreted as fixed Morse code characters of the following form: Bits M_0 and M_1 are interpreted as an unsigned two-bit integer with M_0 the most significant bit. The value of the integer equals one less than the sum of the number of dots and dashes in the desired Morse character. For bits M_2 through M_5, a one is interpreted as a dash and a zero is interpreted as a dot in the Morse code character. M_2 is the first character bit to be transmitted, followed by M_3, and so on. Only the number of dots and dashes indicated by bits M_0 - M_1 as explained above are used in the generation of the Morse code character--any remaining bits are ignored. The following are examples of the message coding:

Signal	M_0	M_1	M_2	M_3	M_4	M_5
• –	0	1	0	1	X	X
• • • •	1	1	0	0	0	0
– • – •	1	1	1	0	1	0
•	0	0	0	X	X	X
–	0	0	1	X	X	X
FIRE	0	0	X	1	1	1
TIME	0	0	X	1	1	0
START	0	0	X	1	0	1
STOP	0	0	X	1	0	0

To protect against noise in the radio link, the on-body logic requires that two successive 16-bit data words be identical before they are recognized as valid. The central station transmits 10 words (header/data pairs) in succession for each operation to enhance the reliability of the data channel. The manner in which all of these features are brought together into a functioning module is illustrated in Figure 3.

D. Central Station

The central control and transmitting station consists of a Motorola transmitter and an SRI-designed control unit. (The Motorola equipment also includes an unused receiver, because it is cheaper to purchase the transmitter/receiver combination than a transmitter only; the receiver may be used in subsequent development activities.) The transmitter carrier frequency is 170.4 MHz in conformance with the frequency assignment obtained by NASA Ames Research Center. This frequency has been made available to this project in the Ames/SRI region and at Sands Point, New York. The transmitter is rated at 10 W output, which should be more than adequate to cover the three concrete-and-steel buildings on the wooded site of the National Center's new facility in Sands Point. (A trade-off between

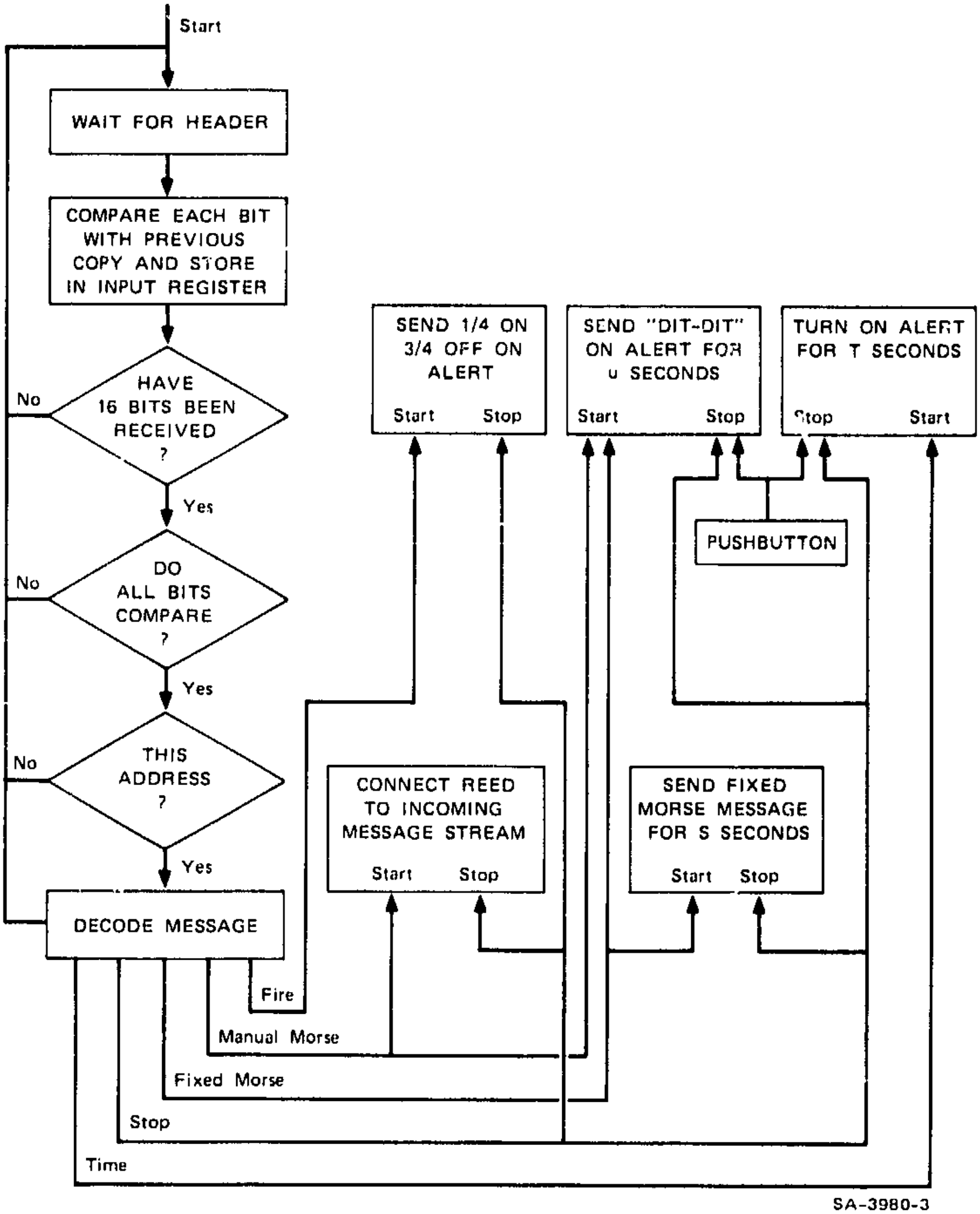

FIGURE 3 FUNCTIONAL DIAGRAM OF ON-BODY CONTROL LOGIC

central station output power and on-body receiver sensitivity will be exploited in later work.)

The input to the transmitter is via cable from the control cabinet (see Figure 1); the input signal is generated in an FSK tone modulator housed in the cabinet. The two tones are 1650 and 1178 Hz, and the frequency deviation is 3.3 kHz. The FSK audio signal frequency modulates the carrier of the transmitter (resulting in a frequency modulated subcarrier that frequency modulates the main carrier). Although a phase-modulated carrier has superior noise immunity, this mode would require additional development effort that was judged inappropriate for this model.

The front panel controls (Figure 1) are used by the operator to implement the functions described earlier for the on-body electronics. A toggle switch in the upper lefthand corner selects either the All Receivers or Group addressing mode. A second toggle switch and two thumbwheel switches select the group or individual to be addressed. (The address of the present on-body unit is 1514 and it is a member of Group 5.) The Fire Alarm signal is transmitted to all receivers when the FIRE toggle switch is in the On position, irrespective of the positions of the address selection switches.

In order to initiate the sending of manual Morse code, the BEGIN switch is momentarily depressed to address the selected receiver(s), condition the on-body control logic, and transfer control to the manual Morse binding post terminals. When the terminals are shorted, one of the two tones is transmitted; when the terminals are open the other tone is transmitted. The on-body control logic responds by causing the message stimulator to vibrate continuously as long as the terminals are shorted. This gives the operator complete control over the length of time that represents dots and dashes. At the end of the manual Morse message, the operator momentarily depresses the STOP switch to return the control of the system to its normal mode. The STOP switch can also be used to terminate the transmission of other signals.

The TIME INPUT binding posts are to be connected to a time clock switch to signal the beginning and end of classroom periods, and the like. Shorting these terminals causes the appropriate code to be sent to all receivers. If the time clock switch closes during the time another type of message is being transmitted, the current message will continue, and on completion the Time Period Indication will be sent.

The four pushbutton switches labeled CODE SELECT cause four different single character messages to be transmitted. The meaning of these characters will be assigned by the Center according to need and may be changed from time to time.

The above control functions are NRZI encoded by logic in the control cabinet and fed into the FSK tone modulator.

III STIMULATOR DEVELOPMENT

A. Alert Stimulator

Investigation of various methods for implementing the alert stimulator was the first task undertaken in this project, since less was known about its requirements and options than any other part of the system. Several different types were considered and several experimental models were tested.

Methods of implementing this stimulator can be categorized as either broad-area or localized stimulators. The broad-area stimulators are characterized by low-frequency vibration and by a shaking motion of a large assembly. The method selected for the first model of the system--an eccentric weight on a motor driven rotating shaft--falls into this category. Two other methods in this category--a rotary solenoid and a flywheel device--were considered. In a rotary solenoid, a rotor assembly moves in a circular manner similar to that of an electric motor, but its maximum angular excursion is considerably less than 360°. With a mass attached to the shaft, inertia effects transmit energy into the solenoid mounting structure as the shaft rotates back and forth, and the mounting structure in contact with the skin causes stimulation. In the flywheel device, the flywheel is rotated by an electric motor and energy is stored in the flywheel. The flywheel is suddenly stopped by a mechanical barrier, transferring an energy impulse to the barrier. The reason for considering this method is battery conservation. Both of these methods have merit, and some experiments were conducted; however, further investigation was judged inappropriate because of time and funding constraints and other priorities.

Several localized stimulation methods were considered briefly, and a few experiments were conducted. These methods are attractive because of the potential for low input power--intense stimulation of a small localized area takes less power than moderate stimulation of a large area. The localized stimulation methods are characterized by vibrotactile frequencies in the 100-Hz region, and many of the methods use reciprocating mechanical motion, such as a cylindrical electric solenoid and its inverse (a moving coil, similar to a loudspeaker coil), or a mechanical piston driven by a cam attached to an electric motor. One difficulty these three methods have in common is maintaining continuous contact with the skin while the stimulator assembly is moved from position to position on the wrist, especially with the variety of wrist contours that will be encountered. One method that overcomes this difficulty uses small weights on the ends of "strings" that attach to the rotating shaft of an electric motor. The stimulation is a localized beating type of action, and the distance from the shaft to the skin can shift without interrupting the stimulation. A variation of this method uses brush-like fibers attached to the shaft of a motor or a rotary solenoid. This method achieves stimulation by a rubbing type of action, as does a continuous rubber belt moving over two idlers. All of these localized stimulation methods have merit, but investigation in greater depth would be required to assess them properly. This activity was set aside and the eccentric weight method was selected as adequate for use at this time.

The eccentric weight on a rotating shaft is an effective method of stimulation, although it requires more power than desirable. This stimulator vibrates at 25 to 50 Hz with a shaking motion, and stimulates the skin area in contact with the assembly. Tests were conducted by Dr. Kruger at the National Center to establish its effectiveness and determine the stimulation intensity that should be used. Tests were also conducted (at

SRI) wherein the motor rotational direction was rapidly reversed in an attempt to make the stimulus more distinct; this was judged ineffective.

A life test was conducted on the electric motor to help ensure adequate service life of the alert stimulator. The motor was driven at its rated value of 6 V, and gave satisfactory operation for a period equivalent to about 100 days of normal operation. Driving the motor at 6 V is a worst-case condition, since adequate stimulation is achieved at less than half this value; hence, this performance is probably adequate for the first model. If evaluation of the stimulator in actual use shows service life to be a problem, several alternatives are available to increase lifetime. (The motor used in the first model of the system is a 4-V unit that is otherwise the same as the type that was life tested.)

B. Message Stimulator

In implementing the message stimulator, we have placed the principal emphasis on the cantilevered piezoelectric Bimorph described in Section II, but a small effort was also directed toward other means. The characteristics of the Bimorph as they apply to this application are quite well known from SRI's earlier Optacon work, and in many respects this vibrator is ideally matched to the Wrist-Com requirements.

A notable exception to this matching of characteristics is the Bimorph's resistance to damage induced by mechanical shock. It is inevitable that the stimulator will be subjected to mechanical shock in its normal use by deaf-blind people. Because it is worn on the wrist and because the users are doubly handicapped by being both deaf and blind, the Wrist-Com will probably be subjected to more abuse than is the Optacon. For this reason we have added to the Wrist-Com vibrator a means for limiting its mechanical excursions. A mechanical stop limits the displacement of the end of the cantilevered reed along two axes. The effectiveness of this feature will be tested by actual experience with deaf-blind people using the device. Additional safeguards can be installed if experience shows they are needed.

The vibrator installed in the first model is a single vibrating reed that is bonded by epoxy to a brass mounting mass (approximately 15 g in weight). It will be desirable to reduce the mass of the mount in later models, since the volume and weight of all elements of the on-body unit will become critical when the entire unit is worn on the wrist. A method for reducing the mounting mass is to add a second Bimorph, driven out of phase from the first. This effects a "dynamic clamping" of the vibrators and maximizes the displacement of the free ends. Devices of this type were tested experimentally and their merit affirmed from an engineering standpoint. However, there are some unresolved psychophysical questions that need to be addressed.

When out-of-phase vibrators are used, the most power-efficient implementation uses both vibrators as active stimulators (that is, two out-of-phase pins impact adjacent regions of the finger). An alternative arrangement uses only one vibrating pin in contact with the finger and the second vibrator's only function is dynamic clamping. Using two out-of-phase pins to stimulate the finger and carry the same time-sequential code information, could lead to confusion in interpretation by the user. Preliminary tests conducted by Dr. Kruger showed some people attempted to differentiate between the two pins, rather than treating them as a pair carrying the same information. Further evaluation of this feature is needed before a final decision is made, but for the first model the use of a single vibrator and the resulting increase in mounting mass was judged the best approach.

The single vibrating element used in this model is 24 mm (0.95 inch) long, 6 mm (0.24 inch) wide, and one-half mm (0.020 inch) thick. It is driven by a square wave of voltage at 150 Hz, which is the resonant frequency of the vibrator. A loading mass and the metal pin that contacts the finger are mounted on the end that is free to move. The purpose of the loading mass (2.8 g) is twofold: It lowers the resonant frequency of the vibration, and improves impedance matching between the vibrator and the finger, thereby providing more efficient stimulation. This second characteristic is believed to be correct, but it has not been fully investigated. The reason for decreasing the resonant frequency below its unloaded value is to conserve power. The electrical load the Bimorph vibrator presents to a driving circuit is substantially a capacitive reactance. Each time the capacitance is discharged the energy that was stored must be dissipated in a resistance; thus, to a first approximation, the power dissipated is directly proportional to vibration frequency. The sensitivity of the finger to vibrotactile stimulation is substantially constant between 100 and 300 Hz, permitting the lower-frequency region to be selected.

There is another loading reactance in addition to the loading mass and the finger load in this Wrist-Com implementation: namely, an elastic component introduced by a water seal around the stimulator pin. The pin protrudes through a small hole in the cover of the stimulator assembly to permit access by the finger. An elastomer is bonded to the pin and to the cover to prevent water from entering the stimulator assembly through this hole. The elastomer is acoustically lossy and reactive, and it increases the resonant frequency. The cover of the stimulator assembly is also sealed to the base plate (that lays on the wrist) by means of a rubber adhesive to prevent water entering either the alert or message stimulator compartments.

IV CONCLUSIONS

A combination of commercially available equipment, and custom designed electronic circuits and electromechanical transducers have been successfully integrated into a first model of a tactile paging system. Minor deficiencies in this implementation should be corrected in subsequent models, and some modifications and additions of a significant nature (miniaturization, power reduction, and duplex communication) will require additional engineering effort before the full impact of this system can be assessed. An iterative process of engineering research and development followed by testing in simulated and real-life conditions is an effective means for developing aids for the handicapped, and this method is planned for the Wrist-Com. The first model will now be used to obtain psychophysical data with clients of the National Center for Deaf-Blind Youths and Adults acting as test subjects. The knowledge gained from these tests will aid in specifying characteristics and in establishing priorities.

In developing this model, we have attempted to keep the requirements of the entire system constantly before us and optimize the system rather than perfecting individual elements of the system. This objective is in concert with NASA's desire to obtain useful hardware at the end of this first phase of the project, since the funding for subsequent work is not ensured.