CR 152332

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A TACTILE-OUTPUT PAGING COMMUNICATION SYSTEM FOR THE DEAF-BLIND

By James A. Baer

December 1979

Prepared under Contract No. NAS 2-8711 by
SRI International
Menlo Park, California

for

AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ACKNOWLEDGMENT

The Wrist-Com project was initiated because NASA responded to a humanitarian need presented to them by Frederick M. Kruger, Director of Research, the Helen Keller National Center. Dr. Kruger conceived the idea of the communication system, designed initial feasibility hardware, and served as an advisor to NASA throughout the project. NASA personnel directly involved in the project are Herbert L. Holley, James L. Jones, and Robert R. Zimmerman, who have individually and collectively made valuable contributions to the success of the project.

Many people at SRI have directly contributed to this work, but because the list is lengthy the specific contributions made by each individual are not described. The project team members are: Dayton B. Bell, C. Bruce Clark, Thomas J. Drewek, James C. Gaddie, Leonard S. Gasiorek, John P. Gill, Nickolas P. Krea, Russell, T. Wolfram, and John M. Yarborough. For a project of modest size, this surprising number of people attests to the range of expertise needed for this undertaking.

Organizational structures are needed to carry out work of this kind, which has ranged from establishing psychophysical human factors like tactile-information rate and signal intensity, to such technological matters as obtaining a radio frequency assignment dedicated to this project and developing a compatible radio-frequency/digital-microelectronics interface. Three organizations have been involved--NASA, the Helen Keller National Center, and SRI--and it has sometimes been difficult to achieve a consensus concerning methods and activities to be undertaken. But the generally useful actions that resulted are evidenced by the achievements to date. It is also evident that much more can be achieved after field testing and evaluation.

Because of the altruistic nature of this project, the author is keenly aware of, and grateful for, the more than common amount of interest, voluntary assistance, and general goodwill of many SRI people both at the working staff level and administrative levels.

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 Helen Keller 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. 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). 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. If a client of the Center needs assistance because of a personal emergency, this system provides a means for requesting aid. A final system is planned that will allow 100 or more 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 vibrotactile signals, transmitted to either the user's wrist or finger. The signals are generated in a microcomputer-controlled on-body unit that responds to coded radio transmission signals originating at a base control and transmitting station. This system is referred to as the "Wrist-Com" by Dr. Kruger; the name signifies communication by means of a wrist-worn unit. 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.) This single frequency is used for two-way transmission to and from the base station on a time-shared basis. The timing of the transmissions in both directions is determined by the base-station control unit.

A model of the system has been developed by SRI over a several-year period in several stages. The National Center has largely determined the functions the system is to perform and the priority for their implementation, with NASA and SRI participating in these decisions. The National

Center has tested special test modules and the entire system as it progressed through its development stages.

The hardware that has been developed 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--PHASE ONE

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 base 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 base 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 x 60 x 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.

Figure 2 demonstrates the on-body module as worn for testing and evaluation. The index finger of the right hand in this illustration is in contact with one of the stimulators and is ready to receive tactile information.

B. Stimulator Assembly

The stimulator assembly in Phase One consisted 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)--is too high to permit a reasonable battery life. Because of the power level required by this stimulator, a dual-stimulation method has been developed; furthermore, the slow signaling speed of the alert stimulator limits its utility. The (relatively) high-power alert stimulator is used for some functions; a lower-power message stimulator is used for other functions. The relatively infrequent use of the alert stimulator--partly because of the dual-stimulator implementation--results in an average power required to operate the alert stimulator in the 2- to 5-mW region.

The alert stimulator transmits three different codes to the user representing "fire alarm," "message ready" (indicating that coded information is present at the message stimulator), and a "time signal." The time

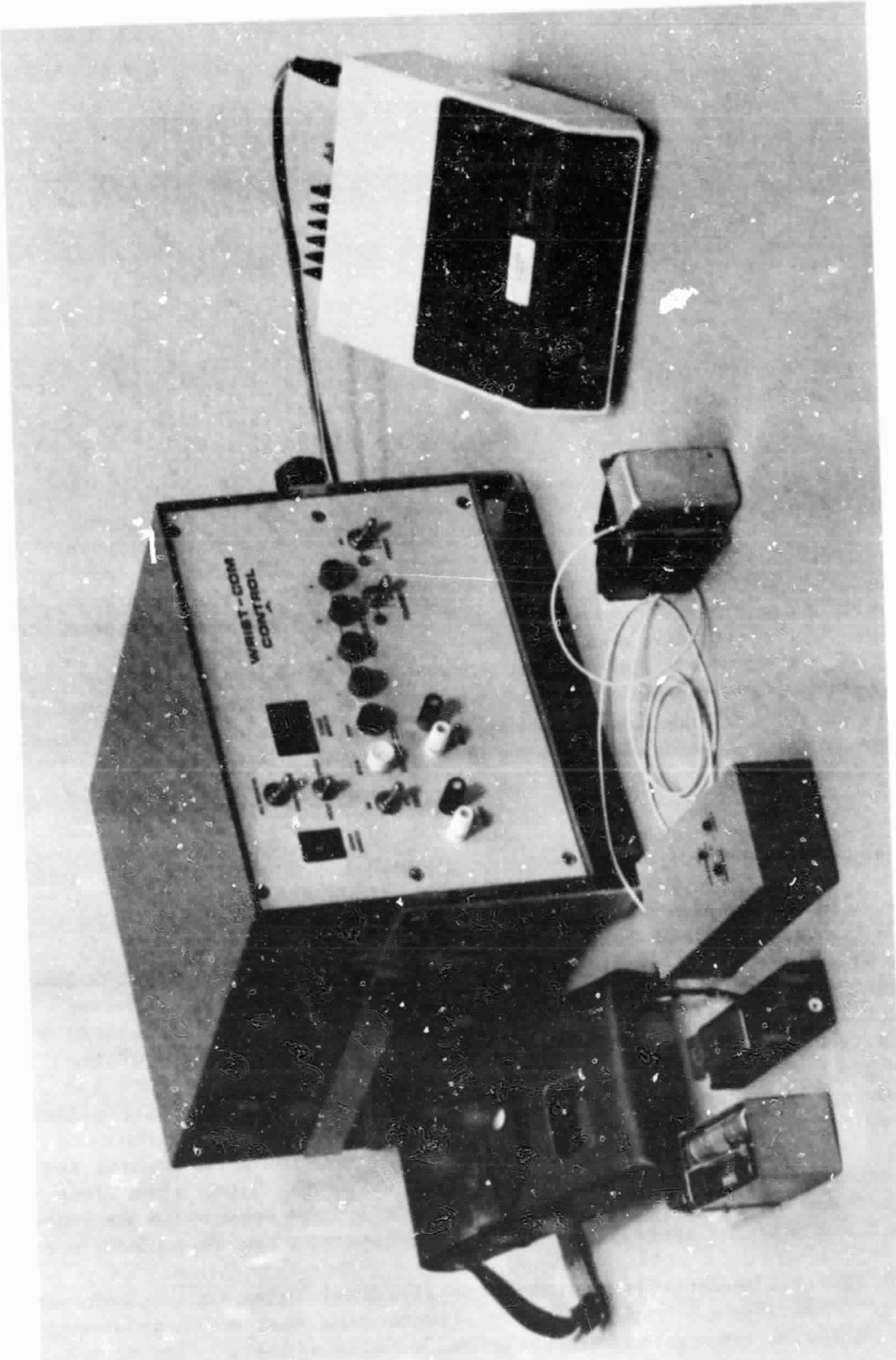

FIGURE 1 FIRST MODEL OF TACTILE PAGING SYSTEM

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FIGURE 2 SIMULATED USE OF TACTILE PAGING SYSTEM

signal will be turned on periodically to indicate the beginning and end of classroom training sessions and break periods.

The alert stimulator is turned on automatically by the on-body electronics in response to the base station, and no action is required by the recipient of the message, other than interpretation. 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 turning on and off the alert stimulator 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. (These intervals were changed in Phase Two.) A pushbutton switch permits the user to terminate the time period indication and message-ready 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-ready 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 to save 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. (The optional termination of the alert signal by the user was eliminated for the Phase Three implementation in favor of automatic termination.)

(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. In the current implementation four such characters can be encoded and transmitted by the base station for tactile presentation to the user. Note that this is a single-character "message"--this mode is not intended for sending messages at the word and sentence level. The meaning of each single-character "message" is to be assigned by the Center as needs dictate. Later versions of the system will have more than four characters. (The on-body unit can respond to the full Morse-code alphabetic character set.) The second type of message is a string of Morse-code characters, sent by the base 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 real-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 vibrating 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 was the primary motivation.

The piezoelectric vibrator in the message stimulator provides a more intense stimulation than does a single vibrator in the Optacon. Information redundancy inherent in the operation of the Optacon is not present in the Wrist-Com, which partially explains 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 users 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

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[1]Baer, J. A., 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).

is represented by long and short periods of vibration for a dash and dot, respectively. The power required to drive the 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 was provided by series-connected 30-V and 15-V batteries. A switch was available for the user to change from 45 V to 30 V for the Bimorph charging source; this provided high- and low-intensity stimulation for experimental purposes during Phases One and Two.

The codes available from the message and alert stimulator in Phase One 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 Ready--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.

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 was a portion of a commercially available paging receiver made by Motorola. All of the receiver package was retained in the Phase-One model, although only about one-third of the internal volume was 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 Phase-One design was retained in Phases Two and Three.

The control logic input is the binary voltage derived from the demodulator, and the output of the logic controls the alert and message stimulators. The digital code structure[2] and the control logic have been

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

designed for reliable operation and minimum parts count. The so-called "Non-Return-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 to the on-body unit is formatted by the base station into 26-bit words. Each word contains two parts: a header and the data. The header is always a succession of nine logical ones followed by a single zero; the data word is carried in the succeeding 16 bits representing 9 bits of address code and 7 bits of message code. To protect against noise and fading 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 basic format of the data stream and protocol developed in Phase One has been retained in an expanded form in Phase Three. The details of the format in its expanded form are given in the Appendix of this report.

D. Base Station

The base control and transmitting station consists of a Motorola transmitter and an SRI-designed control unit. 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 adequate to cover the three concrete-and-steel buildings on the wooded site of the National Center's facility in Sands Point.

The input to the transmitter is via cable from the control-unit enclosure (see Figure 1); the input signal is generated in an FSK tone modulator in the enclosure. 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. A toggle switch in the upper lefthand corner selects either the "all units" or "group addressing" mode. A second toggle switch and two thumbwheel switches select the group or individual to be addressed. The fire alarm signal is transmitted to all units 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 on-body unit(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 on-body units. 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 an expanded set 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 enclosure and fed into the modulator.

III STIMULATOR DEVELOPMENT--PHASE ONE

A. Alert Stimulator

Investigation of various methods for implementing the alert stimulator was the first task undertaken in Phase One of 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--an eccentric weight on a motor-driven rotating shaft--falls into this category. Two other methods in this category were considered--a rotary solenoid and a fly-wheel device. 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 power conservation. Both of these methods have merit, and some experiments were conducted; however, further investigation was judged inappropriate because of 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. These three methods have in common a difficulty in 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 to 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 placed the principal emphasis on the cantilevered piezoelectric Bimorph described in Sections II and VII, 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 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. In the Phase Three implementation an elastomer diaphragm serves this function in addition to sealing against water.

The vibrator installed in the first model was a single vibrating reed bonded to a brass mounting mass (approximately 15 g in weight). It was recognized that it would 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 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, some unresolved psychophsyical questions 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. For the first model the use of single vibrator and the resulting increase in mounting mass was judged the best approach, and this question has not been subsequently reconsidered.

The single vibrating element (piezoelectric bender) used 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 as shown in Figure 3. The purpose of the loading mass (2.8 g) is twofold: It

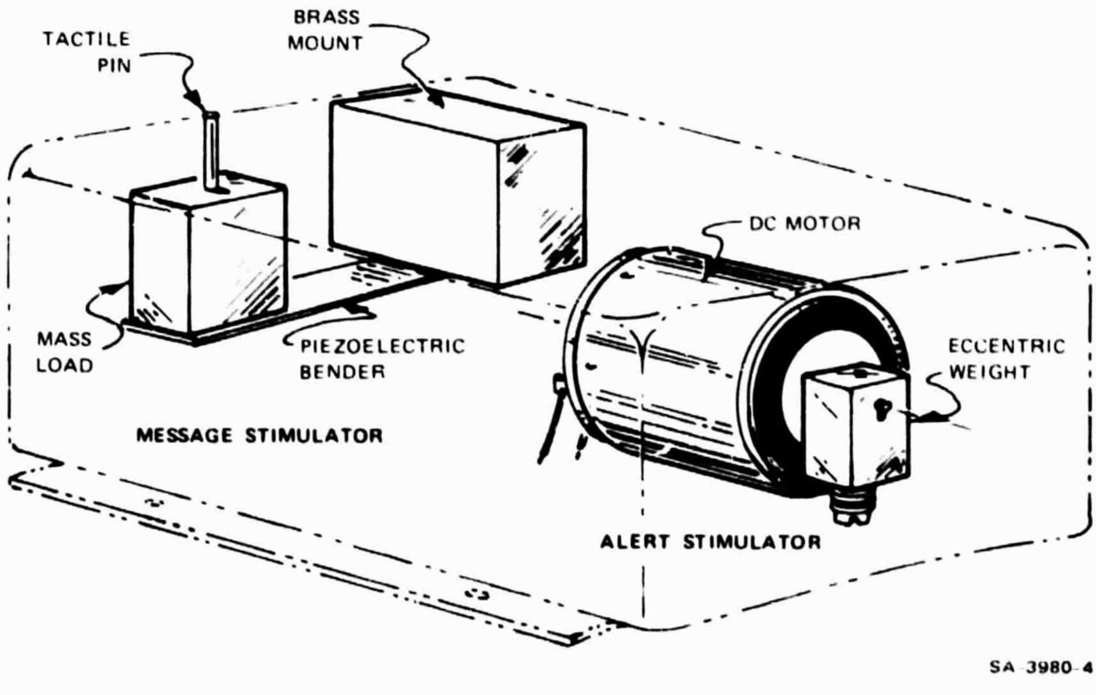

FIGURE 3 TACTILE STIMULATOR ASSEMBLY

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 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.

Another loading reactance in addition to the loading mass and the finger load is 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 THE PHASE-TWO SYSTEM

Phase Two augmented and improved the functions of the breadboard system developed in Phase One. During this phase the system was modified as follows:

- Certain aspects of the control logic for the base station and the on-body unit were improved, and some temporary modifications were added to the on-body unit to facilitate testing at the National Center.
- An on-body FM transmitter was developed to provide a significant new function to the system, namely, two-way communication. This transmitter is a small, low-power, battery-powered unit, and it was the basis for the transmitter included in the wrist-worn package developed during Phase Three.
- The problems of miniaturizing the on-body control logic to make it suitable for inclusion in a wrist-worn package, which have been significant problems since the outset of the project, were addressed, and a course of action proposed.

The following components of the system were not modified:

- The stimulator assembly was not changed, although some improvements would be beneficial.
- The radio frequency (RF) portions of the system associated with the one-way transmission feature were not changed. The present model operates satisfactorily at a frequency of 170.4 MHz--a government frequency assignment obtained by NASA for system development purposes.

V NEW FEATURES--PHASE TWO

A. General

The features added to the breadboard hardware during Phase Two of the program are of two types: candidates for inclusion in the final version of the system, and features that were included temporarily to facilitate the specifying of vibrotactile signaling parameters. The parameters are mainly timing intervals of the time-sequential codes for the alert and message stimulators. The Phase Two features that are included in the Phase Three version of the system are: an on-body radio transmitter, a base station demodulator, and certain additions to the control logic in the base station and the on-body unit. The on-body transmitter, which is discussed in Part B below, is the most significant feature from an overall system point of view. The control logic modifications although time-consuming to implement and essential to the system, are somewhat difficult to appreciate without a detailed step-by-step description that would not be appropriate for this report. The temporary logic modifications and those for the final version are discussed in Part C of this section.

B. Two-Way Communication

One-way communication, from the base station to an on-body unit, was implemented in Phase One. Extending the operation to two-way communication required an on-body transmitter and antenna, a base station demodulator, and control logic additions. The description that follows relates primarily to the on-body transmitter.

The transmitter will be used to request aid in the event of an emergency and to acknowledge that a message addressed to a specific individual has been received and understood. The transmitter consists of a crystal-controlled two-stage VHF radio frequency generator, which is frequency-modulated by an audio tone oscillator and coupled to a wrist-strap antenna.

In the RF generator, the first stage is a single transistor crystal oscillator operating at 85 MHz with a third-overtone quartz crystal. The oscillator output drives the second stage, a two transistor frequency doubler, which produces a 20-mW output signal at 170 MHz. This output is coupled through a 3-dB attenuator to the wrist-strap antenna. The attenuator reduces antenna mismatch effects on the doubler operation. The tone oscillator uses two micropower operational amplifiers in a clipper-filter arrangement that requires no additional circuitry for amplitude stabilization. The sine-wave output signal drives the tuning diode in the RF crystal oscillator to produce a frequency deviation of ±1.5 kHz. This is doubled in the second RF stage to produce an output deviation of ±3 kHz. The total power consumption of the circuitry using a 5-volt power source is 50 mW.

The wrist-strap antenna provides a novel means for the transmission of radio signals by on-body devices such as this wrist-worn transmitter. The antenna itself is the human arm. A wrist-strap device is used to couple radio energy to the arm "antenna." This coupler consists of two rectangular strips of copper foil enclosed in an insulating wristband. One strip is connected to the transmitter's metal enclosure, which is connected internally to the ground or common side of the circuitry. The RF energy is capacitively coupled from the copper strips to the arm. The impedance looking into the wrist-strap coupler varies somewhat from person to person but is usually in the range from 40 to 60 ohms, with only a small reactive component. It is thus a good match to the 50-ohm output impedance of the transmitter RF circuitry.

A test version of the transmitter was fabricated using miniature electronic components mounted in a small metal enclosure. This test transmitter is shown in Figure 4; the white wristband contains the copper foil strips for the antenna. Field tests were made at the SRI building complex using the test transmitter, wrist-strap antenna, and a base receiver with a ground-plane monopole antenna 30-feet high. Very good outside coverage was obtained to at least 1200-feet separation. Coverage inside buidings varied from very good to poor depending upon the type of building construction and the location within the building. The Phase Three miniaturized version of the on-body unit includes this transmitter in a repackaged module.

The following characteristics and protocol were established for two-way communication:

General

- A single frequency assignment will be shared by the base station and wrist transmitters, 170.4 MHz. All signals from on-body transmitters to the base station will have the same characteristic, namely, a carrier with a single frequency tone that is frequency modulated onto the carrier.
- To acknowledge receipt of a message the user will depress a switch button once.
- To request aid at any time the user will depress a switch button three or more times in succession (the same button as for the acknowledge).
- Periodically and automatically the base station will test the operational status of the on-body unit(s) by requesting a transmission from the on-body transmitter. This action will be transparent to the user.

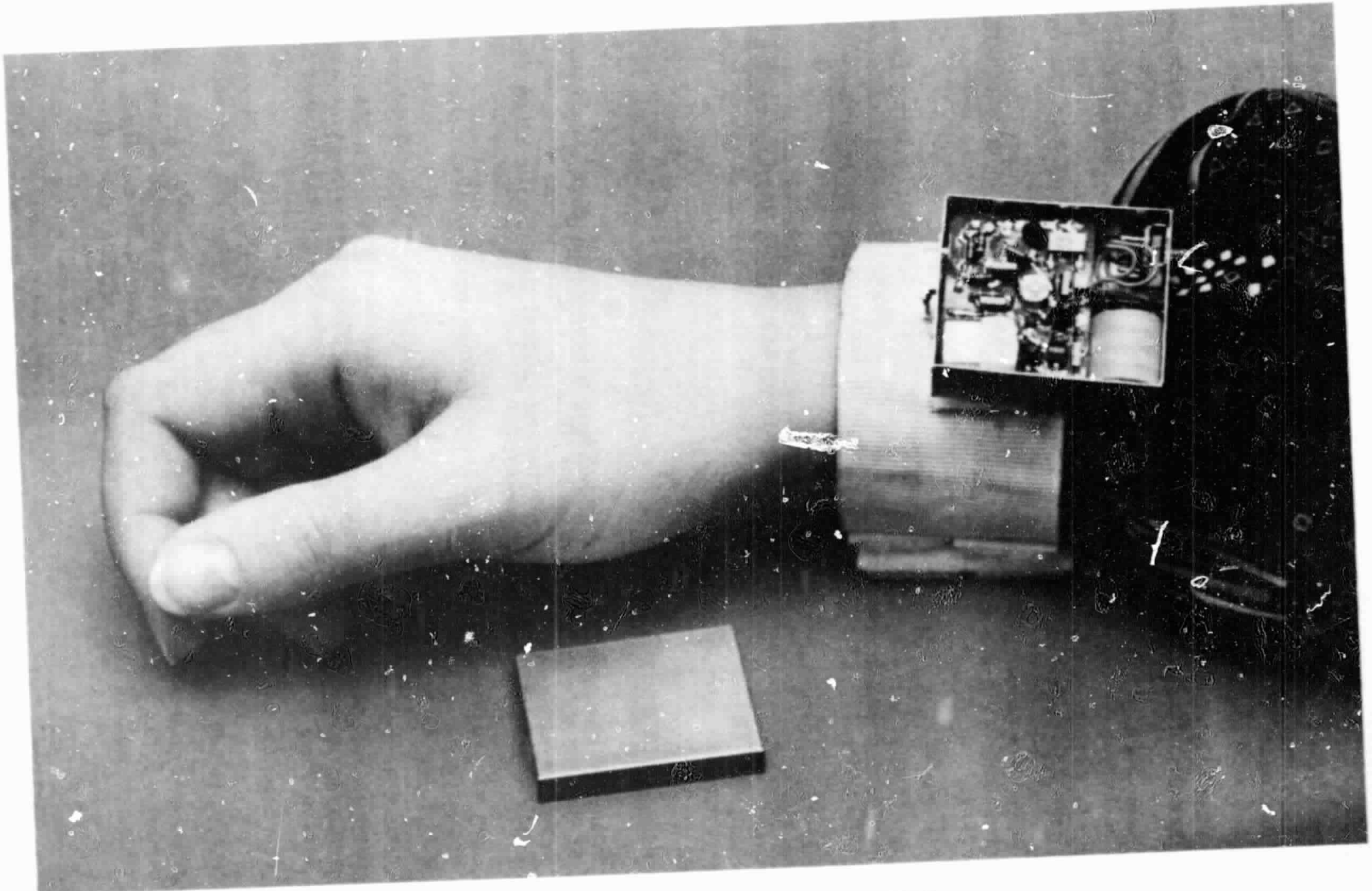

FIGURE 4 WRIST-WORN TEST TRANSMITTER

"Acknowledge" Sequence

- After the base station sends a single-character Morse code message to a selected individual, the base station will automatically interrogate the addressed receiver and request an "acknowledge" signal (acknowledge interrogation mode).
- When the user understands the message and depresses the switch button, a status flag is set (the "acknowledge status" flag).
- Upon receipt of an interrogation code from the base station the on-body unit automatically tests its status flag. If the flag is set, the on-body transmitter will be turned on to indicate the message has been received; that is, message acknowledged.
- Upon receipt of the signal from the on-body unit, the base station responds with a coded signal that resets the acknowledge status flag.
- If the switch button is depressed while the alert stimulator is sending vibrotactile code (message ready only), the alert stimulator is turned off and the message stimulator is turned on. (Note: This feature was subsequently deleted.)
- If the button is depressed indicating receipt of message while the message stimulator is still presenting the vibrotactile code, the stimulator is turned off in addition to the setting of the status flag.

"Aid-Request" Sequence

- When the base station is not sending a message under the control of an operator or the time clock, and it is not in the acknowledge interrogation mode, the base-station control logic will automatically switch to the polling mode.
- When an individual requests aid (by depressing the button three or more times) an on-body status flag is set (the "aid-request status" flag).
- To detect the fact that an aid request has been made, the base station in its polling mode sends a coded signal successively to each group of users to ascertain the binary state of the aid-request status flag.*
- In response to the coded signal, each on-body unit in the addressed group tests the state of its own status flag, and if in the set state, sends a signal to the base station.*
- When the base station receives a signal from any member of the group addressed, it switches out of the group polling mode and sends a coded signal to the individual on-body units within the appropriate

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*Currently, polling is via individual on-body unit only and not by group.

group. (As before, receipt of the base station's coded signal causes the on-body unit to test its aid-request status flag.)*

- When the base station addresses individually the on-body unit whose status flag is set, that on-body unit transmits a signal to the base station, and this identifies the requestor.
- Upon receipt of the signal from an individually addressed on-body unit, the base station responds with an "assurance message" to the alert stimulator and also resets the on-body aid-request status flag.
- Simultaneous with sending the assurance message the base station control module indicates the existence of an emergency condition to the operator by a suitable alarm (panel lamp and audible alarm), and the panel indicates the address of the requestor.

At the conclusion of Phase Two the Wrist-Com system, including a slightly modified version of the test transmitter, was shipped to the National Center for RF coverage and two-way communication testing. An SRI-designed demodulator was added to the Motorola base station receiver and was included within the enclosure. The system was tested in two modes: one, an automatic-response mode in which the base station operator sent a message to the on-body unit, which then automatically responded with a transmission from the on-body transmitter. (This was accomplished by turning the on-body transmitter on and off in lieu of or simultaneous with the alert stimulator.) An indicator at the base station showed when the transmission from the on-body unit was received by the base station, thus completing the communication cycle. In the other testing mode, deaf-blind people and people with normal sight and hearing wore the on-body unit and were a link in the communication cycle. Upon command from the base station via the message stimulator, the wearer would depress a switch button to turn the transmitter on and then release the switch to turn it off. A subsequent message from the base station operator indicated to the wearer whether or not a satisfactory response transmission was received at the base station.

C. Control Logic Additions

New control logic features were added during Phase Two to both the base station and the on-body unit. Changes in the on-body logic required a considerably greater effort to implement than those in the base station because of packaging restraints (that is, the small size of the on-body unit). Throughout the project the control logic has been an important factor in establishing goals and determining the amount of effort required to pursue these goals. During Phase One a considerable effort was required to provide the necessary on-body control functions using a small number of logic packages (30 14- and 16-pin dual in-line packages). This resulted in a sophisticated logic design that is very effective, although somewhat

*Currently, polling is via individual on-body unit only and not by group.

complicated from a design and understanding point of view. In keeping with this effort to minimize package count, the volume necessary for the wiring of the logic packages was also held to minimum. This was achieved by using magnet wire (No. 36 double-coated film insulation) and wire wrapping directly onto the pins of the packages. This method of fabrication, however, does not lend itself to making retrofit changes in the logic, such as those accomplished during Phase Two.

The logic design and packaging efforts of Phase One made it possible to house the on-body control logic in the metal enclosure shown in Figure 1. The logic required two densely packed boards that were mounted in the enclosure. The enclosure is actually somewhat larger than was necessary for the two boards; it was sized to fit into the leather carrying case. Because of this, the package additions required for the Phase Two version were mounted on a third board that was also put into the enclosure. The logic changes in the base station and the on-body unit required a substantial effort to implement, in part a result of hardware retrofitting. A detailed description of the logic itself is not included here; instead, the following list cites the modifications for both the base station and the on-body unit. The modifications fall broadly into three categories; simplification of the base station operator procedures, simplification of the interpretation required by the user of the tactile output under specific circumstances, and improvement in functional reliability.

- Addition of a clear-to-send indicator for manual Morse code mode.
- Addition of base station switch-opening control of the vibration period for the time period indicator.
- Addition of automatic turn-on and turn-off of the base transmitter under logic control.
- Addition of automatic fire-stop signal to all on-body units.
- Addition of repetitive fire alarm turn on.
- Removal of the spurious vibration of the message stimulator that preceded the alert stimulator message-ready code when in manual Morse code mode.
- Removal of the overlapping vibration periods of the alert and message stimulators.

All of the above modifications were intended to be improvements that would be included in, or at least evaluated for, the final version of the system. In addition to the above listing, four temporary modifications were made in the on-body logic to facilitate testing at the National Center with the aid of deaf-blind people. These modifications permit field adjustment of certain timing intervals as follows:

- Addition of a variable control of the code rate for the fire alarm (alert stimulator).
- Addition of variable control of the code rate for the message-ready signal (alert stimulator).

- Addition of variable control of the code rate for the single-character Morse code mode (message stimulator).
- Addition of variable control of the number of repeats of the message-ready signal (alert stimulator).

The three code rates and the number of repeated signals were adjustable by potentiometers included in the control logic enclosure and accessible from outside the leather case.

Figure 5 shows the rates (determined at the Center) for the message-ready and fire-alarm signals from the alert stimulator, and the approximate tactile sensation. The code assigned to "message ready" is: ON for one unit of time, OFF for one unit of time, ON for one unit of time, OFF for five units of time. Tests determined that this sequence should be repeated once. One unit of time was set to equal approximately 0.4 seconds, as measured electrically using an oscilloscope. However, because of the buildup and decay time of the motor in the alert stimulator, there is no abrupt transition between the on and off condition when sensed tactually. The

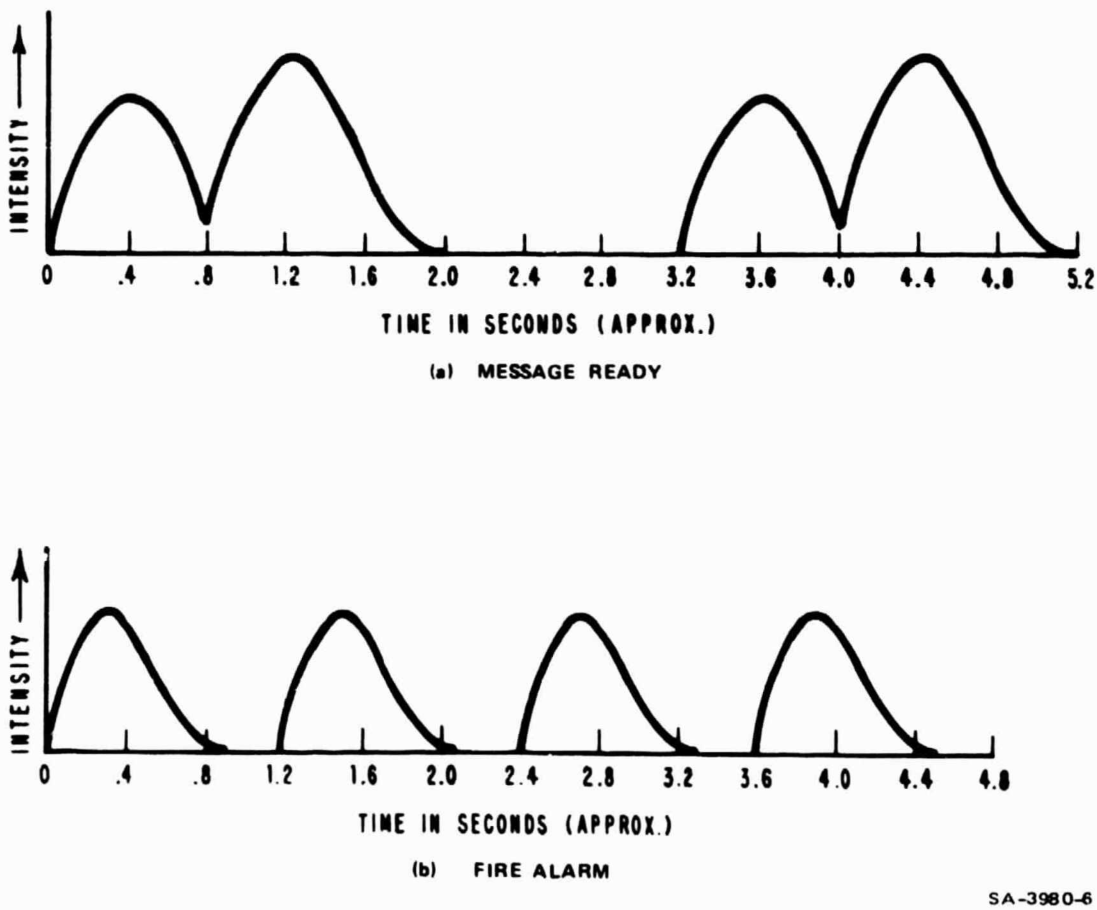


FIGURE 5 ALERT STIMULATOR SENSATION

minimum effective vibration period is approximately 0.8 seconds--the motor does not come to a complete stop during the 0.4-sec off time.

The code for the fire alarm is: ON for one unit of time, OFF for three units of time, repeat for an undefined period of time. (This cycle is briefly interrupted by periodic retransmission of the RF fire alarm bit-stream from the base station.) One unit of time was set to equal approximately 0.3 seconds. However, as for the message-ready signal, the buildup and decay time of the motor influences the tactile sensation. The stimulation intensity for the fire alarm is somewhat less than it is for the message-ready signal because the time allowed for motor acceleration is 0.3 seconds rather than 0.4 seconds. These tests confirmed that the intensity level established for the alert stimulator during Phase One is satisfactory. The two-position intensity switch was set in the low position for the tests at the National Center and the conditions illustrated in Figure 5. (In the Phase Three version of the system the two intensity levels are strap-selectable. Similarly, the rate of the single-character Morse code from the message stimulator is strap-selectable.)

For the single-character Morse code mode (message stimulator), the vibrotactile stimulus representing a dot has a duration of one unit of time and the vibrotactile stimulus representing a dash, following the usual convention, has a duration of three units of time. One unit of time was set at the National Center to equal 0.26 seconds; thus, a dot has a duration of 0.26 seconds and a dash has a duration three times greater--0.78 seconds. The off interval (no vibration) within a character has a duration of 0.26 seconds, and the off interval between repeated characters has a duration of 0.78 seconds. For example, one of the Morse code characters used--message number 1--is the letter "O" (dash, dash, dash), which requires 3.64 seconds, including the 0.78-sec off interval between characters.

It is interesting to note that the minimum timing element for the alert stimulator is approximately three times the value of the timing element for the message stimulator; namely, three-fourths of a second as compared to one-fourth second. The alert stimulator is not capable of operating at a faster rate because of the buildup and decay time of the motor and its eccentric load. The message stimulator, a piezoelectric flexure-mode vibrator, has no tactually discernible buildup or decay time. This speed limitation of the alert stimulator is an additional reason, along with saving battery power, for using two types of stimulators in the on-body unit.

VI ON-BODY MINIATURIZATION--PHASE TWO

From the outset of this project (and in Dr. Kruger's planning before this project was initiated) a major factor has been the requirement that all the necessary functions of the final version of the on-body unit must be implemented in a small package suitable for wearing on the wrist. This puts stringent limitations on the power consumption, size, and weight of each module included in the on-body unit. The modules are the power supply, control logic, receiver, transmitter, and stimulator assembly; each of these can be reduced in size, especially the control logic. The control logic miniaturization to be carried out during Phase Three of the project was studied during Phase Two. Several different approaches were considered, and we concluded that the best approach was to use microcomputer chips in a hybrid package. The possibility of the microcomputer chips in a hybrid package. The possibility of the microcomputer approach was considered duing Phase One but, at that time, it would have been a higher-risk and more-costly approach than hard-wired logic, partly because of the state of development of CMOS (complementary-metal-oxide-semiconductor) microcomputer technology.

The first possibility we investigated for miniaturizing the control logic was the use of a semicustom LSI (large scale integration) chip. A fully custom chip was not considered because of the high cost. However, the semicustom chip was also found to be too expensive--$32,550 to a semiconductor manufacturer plus associated SRI costs. Semicustom chips are made by selective masking for interconnection of transistors made on LSI chips in high-quantity production. A manufacturer of these semicustom chips using CMOS technology (for low power) was contacted and a cost and size estimate obtained on the basis of the Phase One logic diagram. It was estimated that the entire logic could be put on a single chip measuring 7.2 by 7.3 mm (282 by 288 mils) and would cost $32,550 for the minimum quantity of fifteen chips. This chip has 1600 pairs of CMOS transistors.

The second approach considered was to obtain in chip form the approximately 30 MSI (medium-scale integration) and SSI (small-scale integration) circuits required to implement the logic, and to package them using hybrid circuit techniques. A manufacturer of hybrid circuits estimated the price at $8000 for a minimum quantity of ten sets, but the set required two hybrid packages, each measuring 5 x 15 x 57 mm, plus an additional allowance for pinouts. This size was judged to be too large.

It was our conclusion that a microcomputer, assembled in a hybrid package, would be intermediate in price and size compared to the above two methods. In addition, it offered advantages in flexibility compared to the other methods. However, it was recognized that the microcomputer approach involved more risk than the other two methods because a proven hardware logic design was available as a basis for these implementations. We anticipated using RCA's 1802 CMOS microprocessor as the basis for the microcomputer, with three additional chips from RCA's COSMAC family probably required.

VII PHASE THREE SYSTEM IMPLEMENTATION

A. Overview of New Features

Three new modes of operation have been added to the system during Phase Three: "aid request," "operational test," and "message acknowledge." Each of these modes requires two-way transmission and makes use of the transmitter designed in Phase Two. The aid-request and operational-test modes are both polling modes. If the system is not responding to a time clock contact closure or an operator-initiated function, the system is automatically in one of the polling modes--usually the aid-request mode.

In the aid-request mode, the base station sequentially interrogates each wrist unit to determine if the user has requested aid. (Only one wrist unit exists now; the base station cycles through and interrogates six units in the present implementation.) If a user has requested aid by depressing a switch button three times (repetition to avoid false alarms), the base station indicates an emergency condition exists by turning on an audible signal, turns on a red lamp on the control panel, and displays a number identifying the person requesting aid. The appropriate action for the base station operator is to dispatch a staff member to help the requestor (by knowing the general location of the person, according to the daily schedule). Following this, the operator sends an assurance message to the requestor indicating help is on the way, and the base station automatically returns to the aid-request polling mode.

Periodically, as determined by an internal clock, the base station will switch to the operational-test mode. In this polling mode, the base station sequentially requests a radio transmission from each wrist unit. If the transmission is received, the wrist unit interrogated is presumed to be operating satisfactorily.

The acknowledge mode is activated only when an individual user has been specifically addressed to the exclusion of other users (that is, when in the "individual-address" mode and not the "group" or "all-units" addressing modes). Under this condition, when the user receives and understands the message, the proper user response is to depress the wrist-unit transmit switch. This sequence of actions sets a flag in the microcomputer, which is then automatically interrogated by the base station to determine the status of its flag. If the flag is set, the base station returns to the polling mode; but if the user did not depress the switch (flag not set) a warning lamp is turned on at the base-station control panel, and the address of the user is displayed. The operator can send the message again or return the system to the polling mode.

Adding these three modes of operation has required significant expansions to the wrist-unit and base-station control capabilities. The expansion of the base station capability is evident by comparing the control panel as shown in Figure 6 with that of Figure 1. The enclosure for the current base-station control unit is the same one used in Phase One, but the enclosure is now used to full capacity. Resting on top of the control unit in Figure 6 is the Motorola transceiver.

The foreground of Figure 6 shows the on-body unit at an interim stage of development. While in this configuration, the system was demonstrated at the Interagency Conference on Rehabilitation Engineering in Washington, D.C., September 1978. At this stage, the on-body unit had two parts, one worn on the wrist and the other, a microcomputer (the larger of the two black rectangular objects), attached to it by a ribbon cable. This version of the microcomputer was fabricated using standard wire-wrap techniques. The small, black rectangular block at the left foreground is a mockup of the microcomputer in hybrid circuit form; the hybrid circuit had not been developed when this photograph was taken.

Figure 7 illustrates the way a Morse-code tactile message is received--by placing a finger on top of the wrist unit to feel the vibrating pin of the message stimulator. The wrist unit, as shown in Figures 6 and 7, is smaller than the final version shown in Figure 8. It was necessary to increase the height of the enclosure to accommodate the microcomputer. It would have been technically possible to design a microcomputer hybrid circuit package small enough to be included in the smaller-sized enclosure; however, it proved to be too costly ($60,000 as compared to $10,000).

The foreground of Figure 8 shows a microcomputer identical to the one included in the wrist unit. The microcomputer consists of two parts: In the immediate foreground are two EPROMs (electronically programmable read-only memories) shown resting on a PC (printed circuit) board; the longer black component is the custom-designed hybrid circuit (purchased from Micronix, Sunnyvale, California). While it is true that this package is larger than desired, the reduction to this extent marked a significant achievement of the project. The hybrid circuit is shown resting on a PC board; the PC boards are used to interconnect the hybrid circuit and the EPROMs, and to connect the microcomputer to other parts of the wrist unit.

In addition to the microcomputer module, the wrist unit in Figure 8 houses the battery, stimulator assembly, radio receiver, radio transmitter, and associated circuits. The receiver is a dissected portion of the commercial receiver used in Phase One; the radio transmitter is a miniaturized version of the test transmitter developed in Phase Two, and the stimulator assembly is a smaller reconfigured version of the one developed in Phase One.

B. Technical Characteristics

In this section, descriptions in greater detail are given for several parts of the system. The operational procedure and the format for the transmitted data are given in the Appendix.

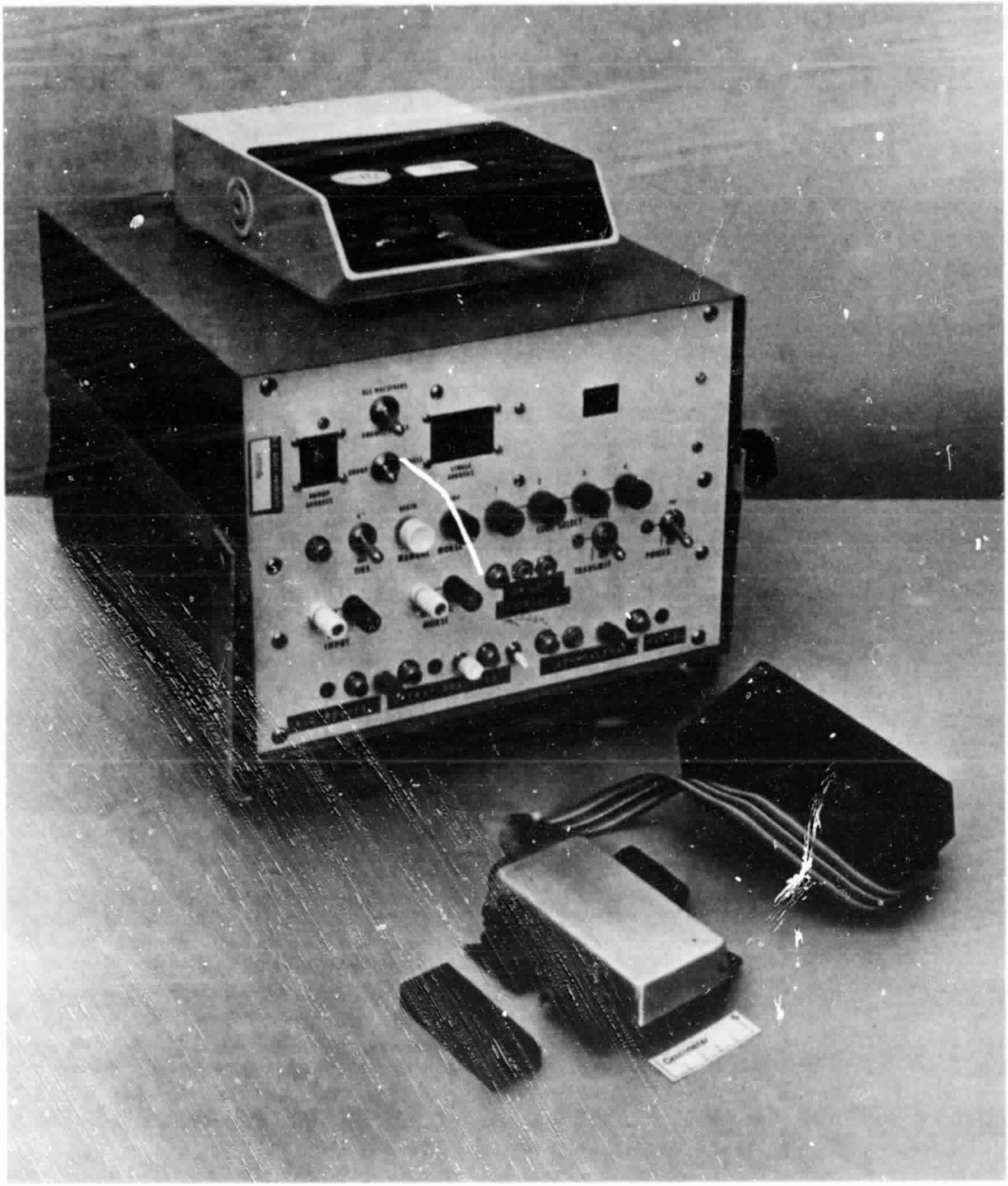


FIGURE 6 SYSTEM AT AN INTERIM STAGE

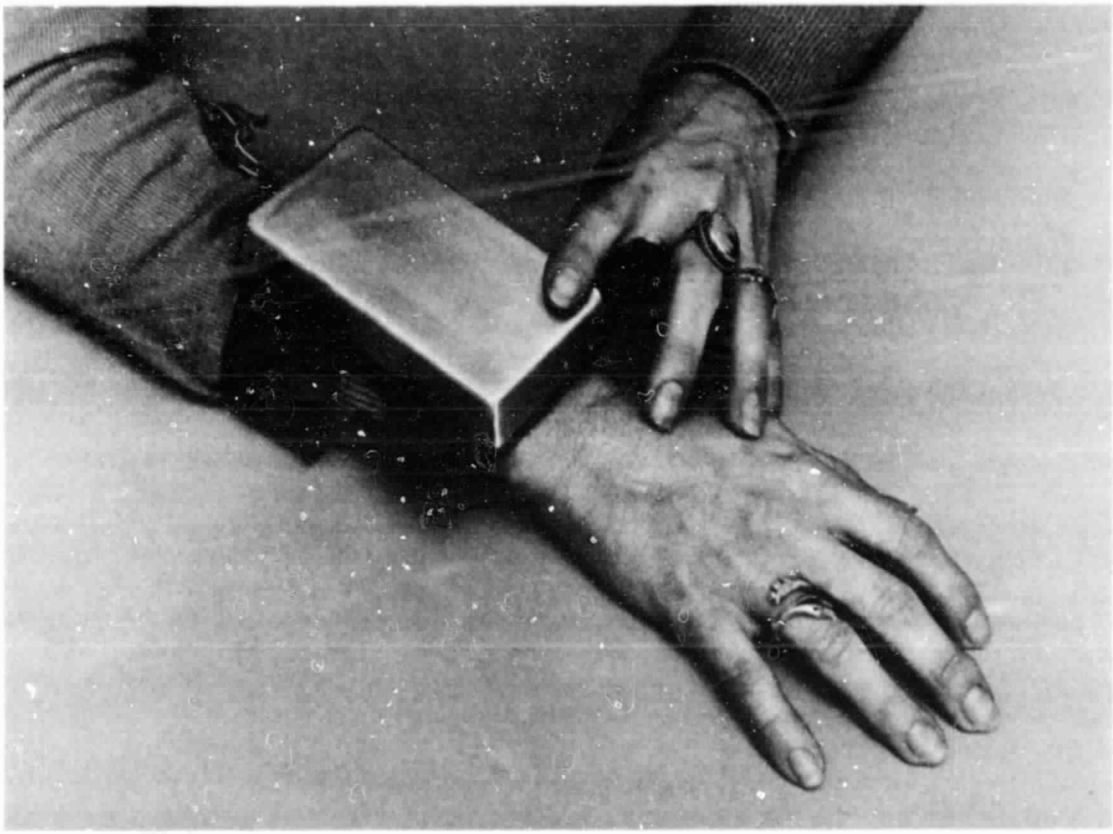


FIGURE 7 RECEIVING A TACTILE MESSAGE

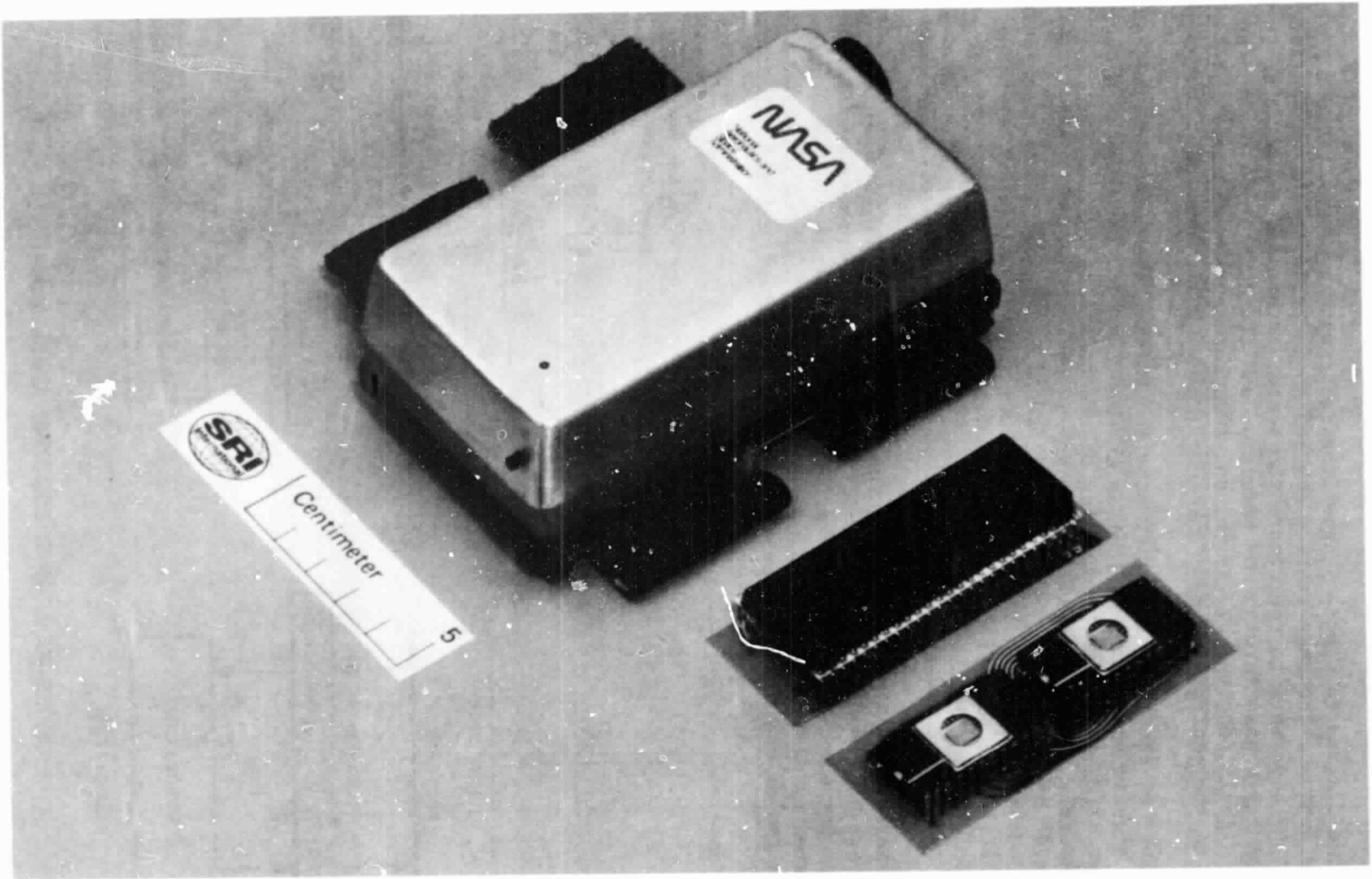


FIGURE 8 WRIST UNIT AND MICROCOMPUTER

1. Overall System and Wrist-Strap Antenna

The diagram in Figure 9 shows the relationship of the various parts of the system. The base-station control logic performs the supervisory functions necessary to coordinate the system. Commands originating in the control logic pass through the modulator and transmitter to the antenna. Radio signals received by the antenna pass through the receiver and demodulator to the control logic.

Most of the time, the wrist unit is awaiting commands addressed to it. Radio signals enter the wrist-strap antenna and pass through the transmit/receive (T/R) switch for processing by the receiver, demodulator, and microcomputer. The microcomputer recognizes when a command is addressed to the wrist unit (address number one for the existing unit) and proceeds to carry out the command. If the command contains a tactile message, the stimulators are activated. If the command requires a response to the base station, the transmitter is conditionally activated and a single-tone modulated carrier is transferred by the T/R switch to the wrist-strap antenna.

The development of the wrist-strap antenna in Phase Two was a significant step, and the gain characteristics at 170 MHz were measured in Phase Three. The measurements were made between two 10-meter high wooden towers separated by 6.25 meters. The signal was transmitted from a person standing on top of one tower and wearing the wrist transmitter and antenna on

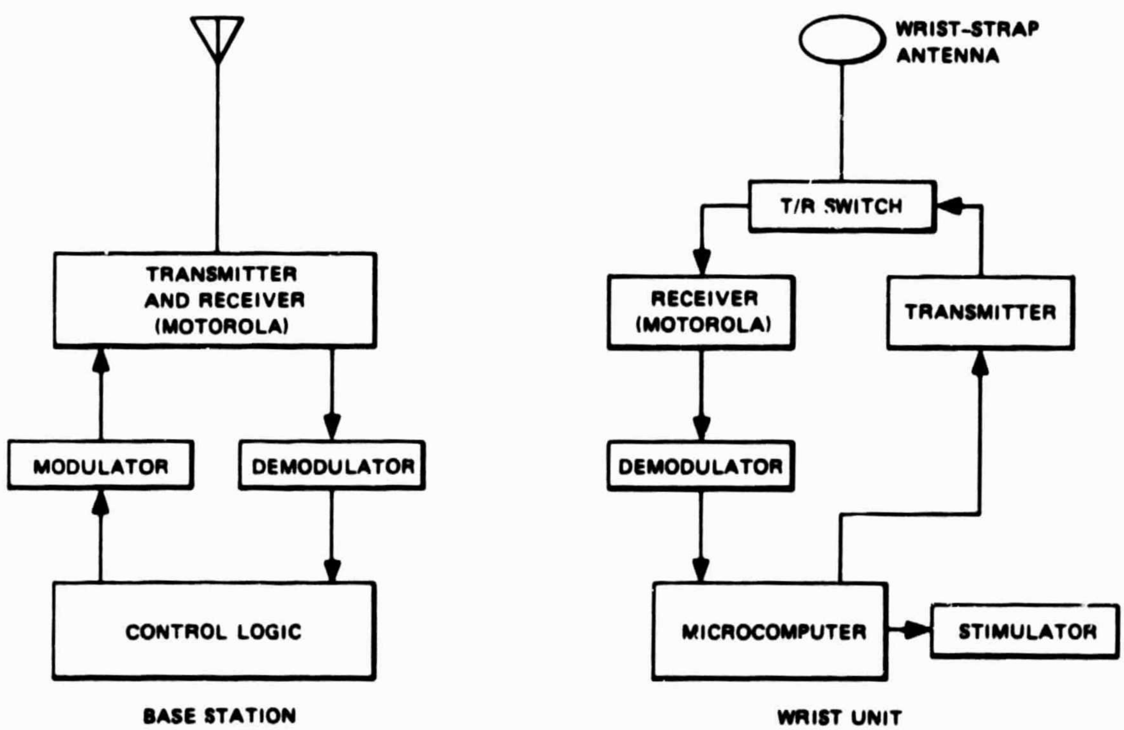


FIGURE 9 WRIST-COM FUNCTION DIAGRAM

the left arm. The received-signal power was measured on the second tower. The receiving antenna on the second tower was a Singer biconical dipole calibrated in terms of gain. The received power was measured using a spectrum analyzer.

Signal levels were measured for several arm positions and body orientations of the person wearing the wrist transmitter and antenna to observe the directivity effects of various body positions. For four body orientations with respect to the receiving antenna--facing, back, right side and left side--data were taken for the following arm positions:

- Left forearm horizontal across chest (position that would normally be used by a person pushing a button on a wrist watch).
- Arms down by sides.
- Left arm fully extended vertically.
- Left arm extended straight out from side horizontally.
- Both arms out to side horizontally.

Signal levels were measured for these positions with the receiving antenna first vertically polarized, then horizontally polarized.

Since the transmitter power, receiving antenna gain, and distance between antennas are known, the following expression can be used to determine the transmitting antenna's gain:

$$Gt(dBi) = 10 \log \frac{Pr(4\pi R)^2}{\lambda^2 Gr\ Pt} .$$

The transmitter power Pt is 6 mw; the receiving antenna gain plus 1.4-dB cable loss is .57 x .72 = .41 = Gr. The antenna spacing, R, is 6.25 meters, and λ = 1.76 meters. Pr is the received power. The maximum received power was -62-dBm (6.3 x 10^{-10}) watts; the maximum gain of the wrist-strap antenna is -32.9 dBi.

The measured gains for the various body positions tested are tabulated in Table 1.

2. Message Stimulator

The major features of the message stimulator as developed during Phase one have been retained in the current version. A notable change is the use of the alert stimulator motor as the mounting mass for the vibrator; an experimental assembly similar to that packaged within the wrist unit is shown in Figure 10. A ferrite transformer for the message-stimulator drive circuit is shown mounted near the motor. Attached to the flat reed is a rectangular brass piece and a pin; the latter is attached to a circular elastomer seal (foreground part of photograph).

Table 1

GAIN OF WRIST-STRAP ANTENNA
170 MHz for Body Orientations
and Arm Positions Indicated
(dB above Isotropic)

Arm Position (Antenna on Left Wrist)	Body Orientation-- Vertical Polarization (dBi)				Body Orientation-- Horizontal Polarization (dBi)			
	Facing	Back	Right Side	Left Side	Facing	Back	Right Side	Left Side
Forearm horizontal across chest	-42.9 -41.9*	-42.9 -42.9*	-44.9 -46.9*	-40.9 -40.9*	-38.9	-50.9	-50.9	-38.9
Arms down by sides	-36.9 -35.9*	-34.9 -34.9*	-36.9 -36.9*	-32.9 -34.9*	-42.9	-40.9	-48.9	-44.9
Left arm fully extended overhead vertically	-35.9	-36.9	-34.9	-34.9	-40.9	-36.9	-45.9	-44.9
Left arm fully extended to side horizontally	-41.9 -42.9*	-41.9 -41.9*	-38.9 -39.9*	-45.9 -42.9*	-32.9	-34.9	-45.9	-52.9
Both arms fully extended to sides horizontally					-34.9	-34.9	-46.9	-52.9

*Measured with wrist strap moved further up arm above wrist.

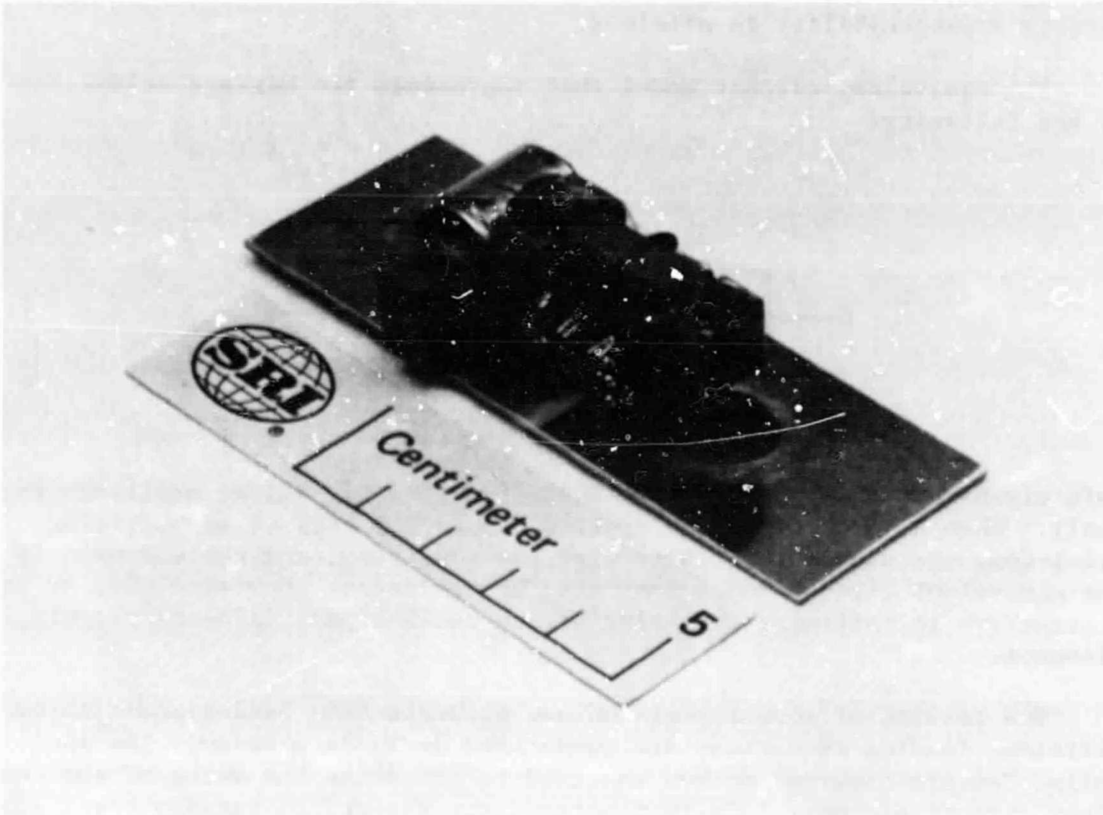
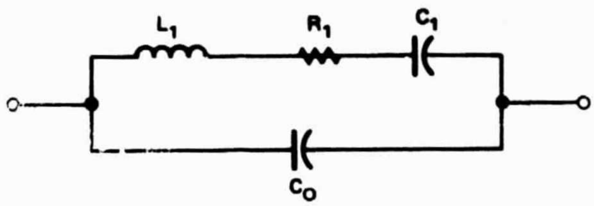


FIGURE 10 EXPERIMENTAL STIMULATOR ASSEMBLY

The motor, or driving element, of the message stimulator is a piezoelectric flexure bender (Bimorph) that responds to electrical input signals; this produces a vibrating motion of the tactile pin to transmit information to the user's finger. The frequency of the vibrating motion is controlled by the electric input signals, and the optimum frequency is dependent upon the mechanical/acoustical parameters of the vibrator and the tactile sensitivity characteristics of the human finger. The vibration frequency we are using is 140 Hz (the Phase One stimulator operated at 150 Hz). By applying and interrupting the 140-Hz input signal, the stimulator is turned on and off in a controlled manner to produce a tactile Morse-code signal that is presented to the user.

The main frequency-determining elements in the message stimulator are the piezoelectric bender, the mass load, the elastomer diaphragm, and the finger of the user. The purpose of the elastomer diaphragm is to provide a water seal between the vibrating tactile pin and the enclosure of the wrist-worn unit. The mass and the compliance of the elastomer, the diaphragm dimensions, and the area of the diaphragm that is bonded by epoxy to the pin are all factors that influence the stimulator resonant frequency. These factors also influence the vibration displacement. The elastomer reduces the vibration displacement and increases the resonant frequency, but the magnitude of these changes is repeatable from unit to unit so satisfactory reproducibility is obtained.

The equivalent circuit model that represents the message stimulator is the following:



This circuit is applicable when the applied electric signal amplitude is small. When a large signal is applied, as is the case in an operating Wrist-Com, the vibrator parameters become nonlinear, and the elements in the equivalent circuit model must also be nonlinear. Nevertheless, it is instructive to determine the value of the small-signal (linear) circuit elements.

The results of measurements on one piezoelectric bender under three different loading conditions are summarized in Table 2 below. The so-called "circle diagram" method was used to determine the value of the equivalent circuit elements. In this method, the electrical impedance (or admittance) of the vibrator as a two-terminal device is measured for a number (10 to 20) of frequencies in the resonance region (mechanical resonance of the vibrator). A plot of the susceptance as a function of the conductance for successive measurements results in a circle from which the equivalent circuit parameters can be determined. For these measurements, a Hewlett-Packard vector impedance meter (Model 4800A) was used. The table also gives the maximum peak-to-peak displacement of the free end of the vibrator, as measured under a microscope, and the vibration frequency corresponding to this maximum displacement when the device is driven by a large signal (nonlinear region of operation). The signal source for the large-signal measurement is an oscillator having a 600-ohm output impedance; it produces a 10-volt rms sine wave. In the table, Q_m is the mechanical Q, f_o is the mechanical resonant frequency, f_{max} is the frequency for which the large-signal displacement is maximum, and D_{max} is the maximum large-signal peak-to-peak displacement.

When a finger is placed in contact with the tactile pin, a reasonably intense tactile sensation is present over a broad frequency range ($\sim$20 Hz) with the center frequency about 100 Hz for this particular vibrator. The peak-to-peak displacement when the vibrator is loaded with a finger is about 0.1 mm (4 mils). When the vibrator is driven at 100 Hz in the absence of a finger load, the displacement decreases to about 0.07 mm (3 mils). This decrease can be explained by the fact that the mechanical parameters of the finger change the effective values of the elements in the circuit model, that is, the finger becomes a part of the vibrating system.

Table 2

VIBRATOR PARAMETERS

Parameter/ Units	Condition		
	No Mass Load	Mass Load Attached (4 grams)	Mass Load and Elastomer Diaphragm Attached
L_1 (Henrys)	59	1500	1600
C_1 (pF)	2700	2900	2200
R_1 (ohms)	2300	11,000	31,000
C_o (μF)	.039	.038	.038
Q_m	64	66	28
f_o (Hz)	399	76	84
f_{max} (Hz)	330	63	73
D_{max} (mm)	.84	.89	.66

The capacitance (compliance) C_1 is substantially the same for all three configurations: This is predictable from theory. Similarly, the inductance (mass) is greatly increased when the mass load is attached to the piezoelectric bender, thus justifying the use of a mass-loaded system.

Adding the elastomer diaphragm (Column four of the table) decreases the effectiveness of the stimulator somewhat; the capacitance C_1 and the resistance (compliance and loss) are the parameters most affected.

The message stimulator requires a special driving circuit. The circuit shown in Figure 11 performs two functions; it generates a square wave and provides an amplitude of 35 volts from a 5-volt dc source. Its operation is dependent on the fact that the loaded piezoelectric vibrator can be approximated in its simplest equivalent circuit analog as the capacitor C_o (the $L_1R_1C_1$ branch is ignored for present purposes). To initiate operation, a pulse stream is applied to points A and B in the circuit. The operating sequence is as follows:

The pulse at A is applied by the microcomputer for a duration of 355 microseconds. During this interval, approximately 4.5 volts is applied across the primary of the transformer, and the current through the transformer adjusts itself to maintain this condition as long as the transformer does not saturate. For the particular design shown here, the transformer saturates in approximately 355 microseconds, thereby providing a volumetrically efficient design of the transformer. In this mode of operation, the Siemens core provides a magnetic flux change of approximately 5 volt-microseconds per turn. (If the pulse duration at A is less than 355

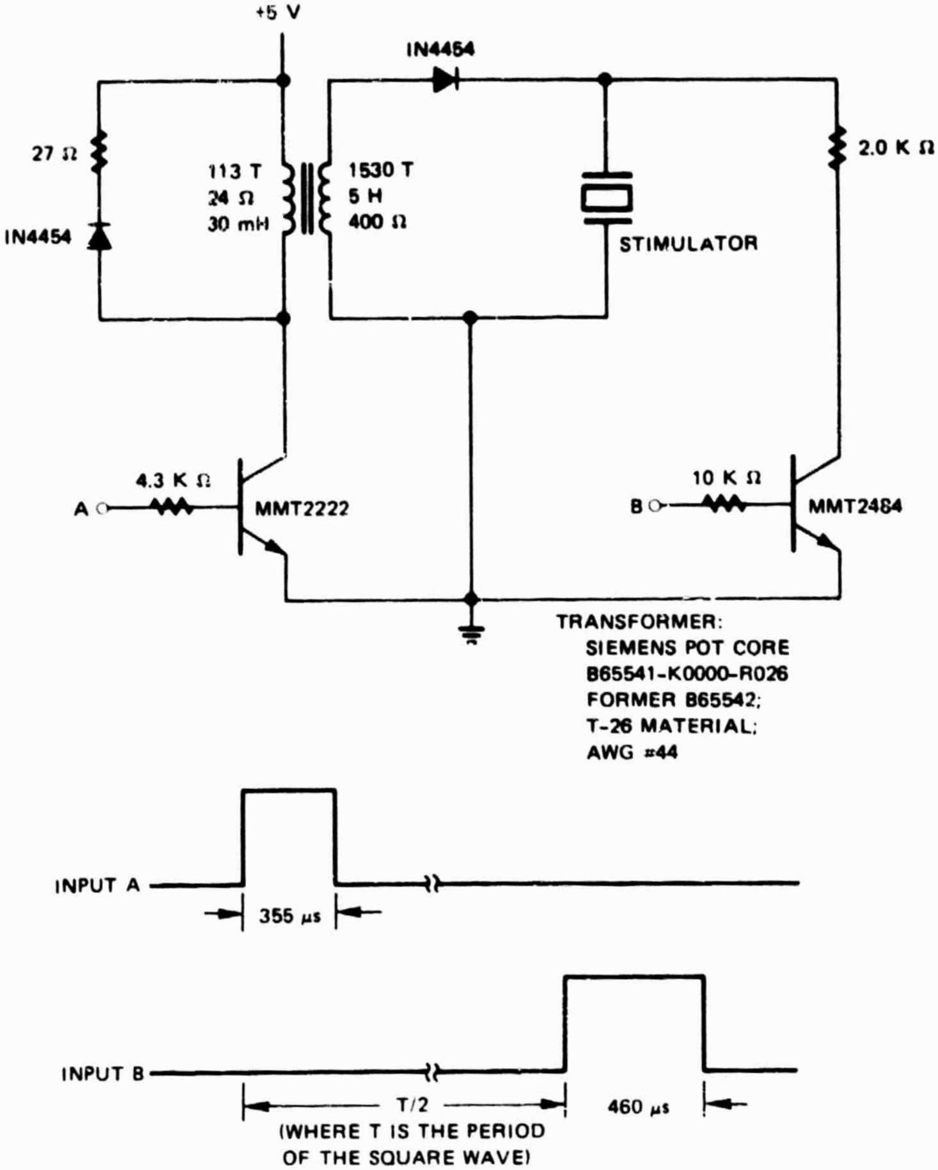


FIGURE 11 DRIVER/STEP-UP CIRCUIT

microseconds, the output voltage across the Bimorph decreases, giving a variable voltage step-up circuit.)

While current is flowing in the primary and the core is not saturated, current flows in the secondary circuit into the Bimorph. During this interval of time, the stimulator presents a capacitive load of approximately 0.03 microfarads to the transformer, and is charged by the secondary current to 35 volts. When transistor A is turned off or the transformer saturates, the secondary current ceases to flow and the diode in the secondary is back-biased--effectively disconnecting the stimulator from the secondary. The diode in the primary circuit is forward biased when the transistor is turned off, and the energy remaining in the transformer is dissipated in the primary circuit resistance.

If the piezoelectric vibrator were a perfect capacitor, it would remain charged (at 35 volts) until a pulse was applied to input B. However, because the electromechanical parameters appear like a series LRC circuit shunting the capacitance (as discussed above) the voltage decreases and the capacitance becomes the energy source for the vibrator.

When pulses are applied alternatively to A and B, a square wave (approximately) is generated. Pulses are repetitively applied to A and B from the microcomputer at a frequency near the resonant frequency of the vibrator for the duration of a Morse code dot or dash to generate tactile code characters. This circuit has proven to be an effective driver for the message stimulator.

3. Hybrid Circuit Microcomputer

The microcomputer configuration is shown in Figure 12, and in Figure 13 a magnified view is given of the hybrid circuit before sealing the package. The hybrid circuit has 50 pins on 2.5-mm centers and measures 2.5 cm by 6.4 cm. The chip set consists of five main chips and three smaller

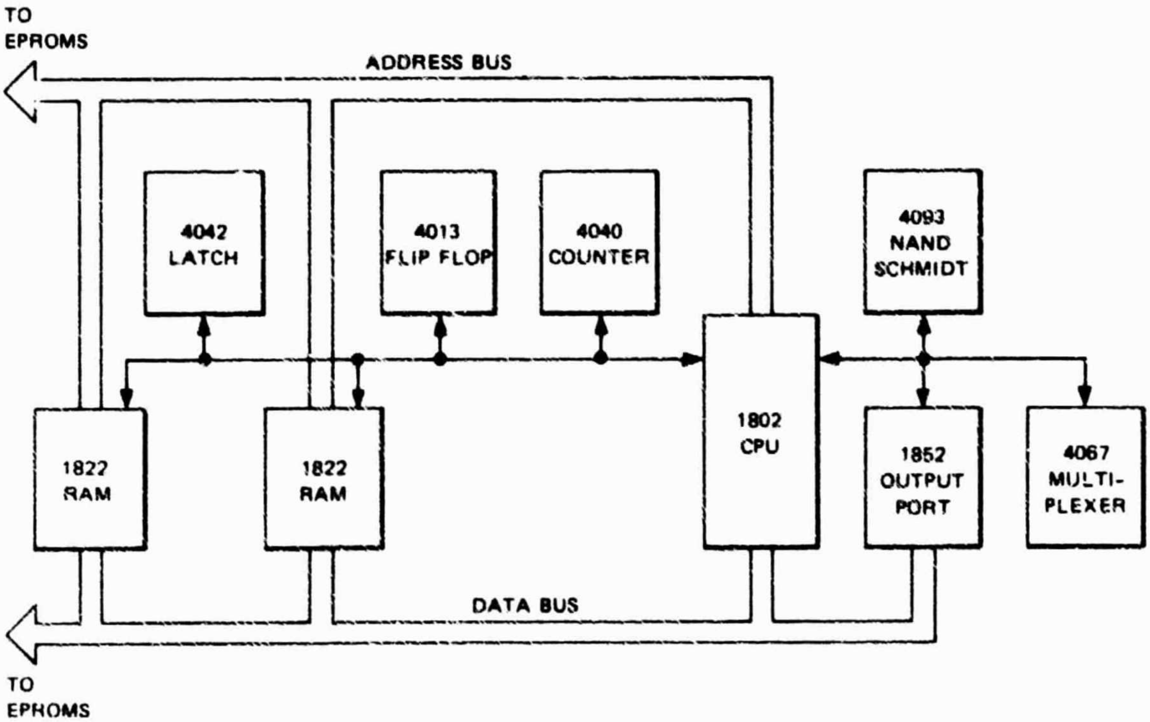


FIGURE 12 MICROCOMPUTER CONFIGURATION

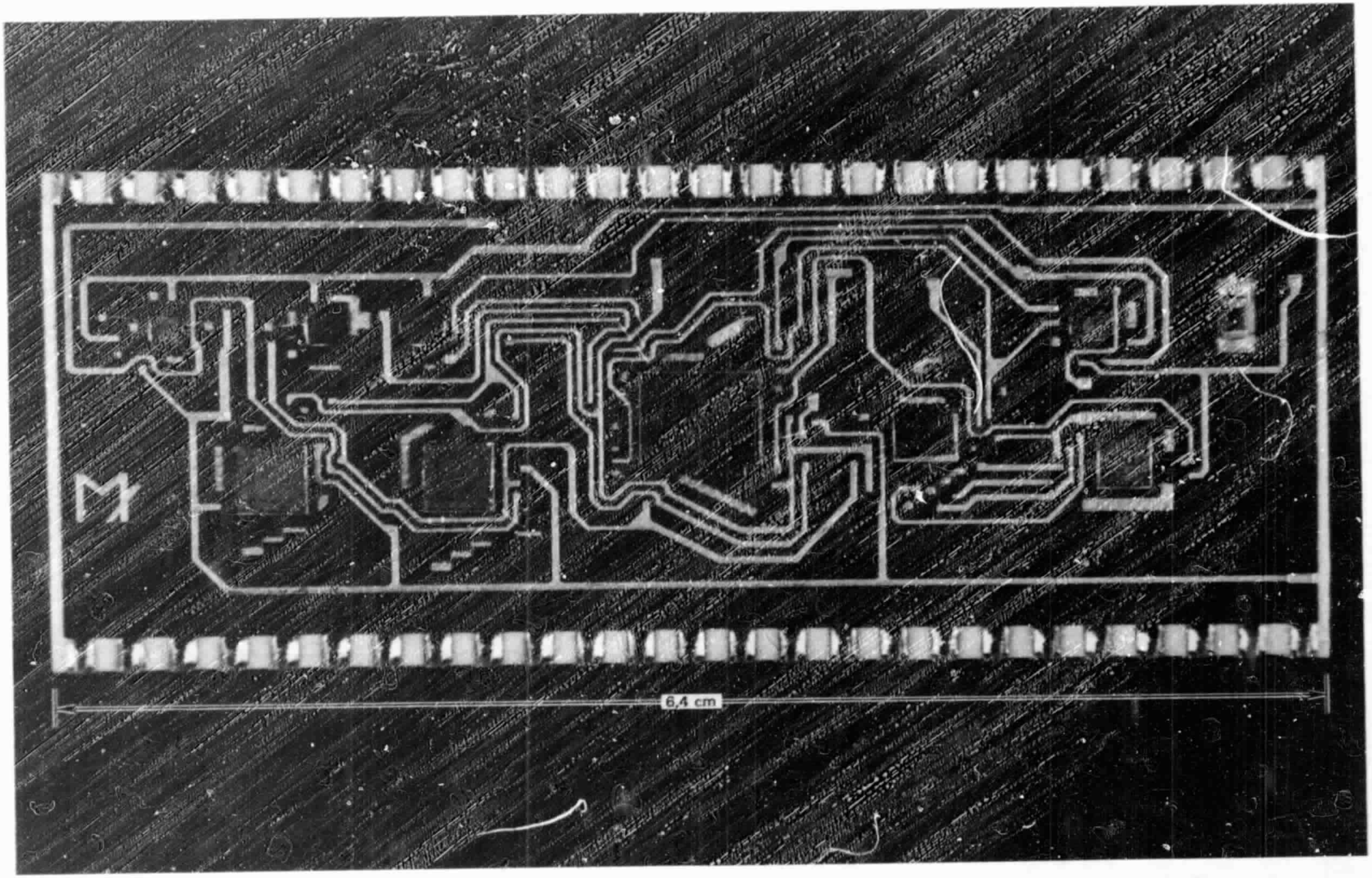


FIGURE 13 HYBRID CIRCUIT MICROCOMPUTER

chips. The microcomputer is based on RCA's COSMAC and uses a CDP1802 microprocessor. A RAM (random access memory) is implemented by means of two 256 x 4-bit memory chips. The CDP1852 is used as an output port to control the stimulators and on-body transmitter, and it also provides a binary input to the CD4067 multiplexer. This single multiplexer chip is used in the place of two input ports, and it provides 12 inputs (16 possible) to the microprocessor through a flag input. These inputs (the wrist unit's individual address, group address, and the single character rate) are needed only once each time the microcomputer is powered up, so the multiplexer provides a suitable method for input and reduces the chip count. The CD4013 dual flip-flop is used to generate the ninth and tenth address bits needed by the memory. The CD4040 counter provides an interrupt to the microprocessor at periodic intervals to enable the subroutine that examines the incoming information from the radio link. Part of the CD4093 NAND Schmitt trigger is used as an inverter for the interrupt signal, and two gates are used to clear the microprocessor during the power-up sequence: the other gate provides a substantially noise-free NRZI signal through a logical AND with a squelch-generated signal. The NRZI signal is the coded data stream and noise from the radio receiver demodulator. (See Appendix for a discussion of NRZI encoding.)

The EPROMs are not included within the hybrid circuit package, in order to permit program changes during development and from time to time as the need becomes apparent. Eventually, it is hoped that they will be included within a hybrid circuit. The EPROMs used are made by Intersil, type number IM6604. This component was the first CMOS (complementary-metal-oxide-semiconductor) EPROM to become commercially available--part of our development work was hampered until it became available. The IM6604 is a 512-byte device, and two of them are required giving a capacity of 1024 bytes. The program uses 90 percent of this capacity. (Intersil has recently replaced the IM6604 with type number IM6654--the components are substantially interchangeable, and both operate satisfactorily in the Wrist Com.) The program flow diagram is given in Figure 14.

4. Wrist Unit Size and Power

It was recognized before this project was initiated that the size of the wrist unit would be a very important factor in the acceptance of this system by deaf-blind people, and, ultimately, in the success of the project. Figure 15 shows the Phase One on-body unit that was worn on the shoulder with a wire connecting to a wrist-worn device. In the foreground is the forerunner of the present wrist unit. (See also Figure 8.) Considerable progress has been made in reducing the size of the on-body unit to an acceptable status; however, it is evident that further reduction is needed. Each of the modules within the wrist unit can be reduced further in size, although the process will be rather expensive.

The approximate relative volume required by each module in the wrist unit is given in Table 3.

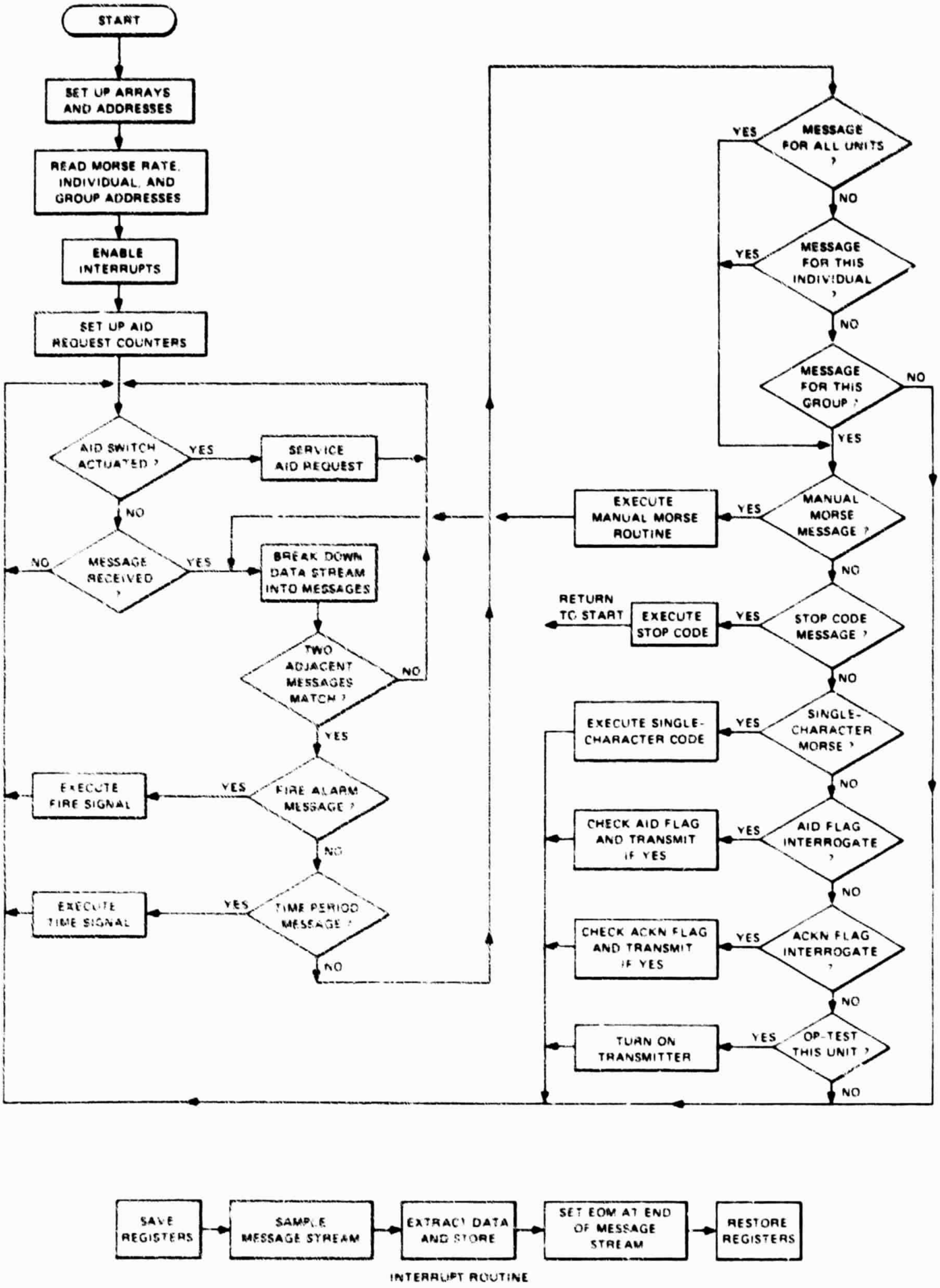


FIGURE 14 FLOW DIAGRAM FOR MICROCOMPUTER

FIGURE 15 TWO ON-BODY UNITS

Table 3

RELATIVE MODULE VOLUME

Module	Total Volume (%)
Microcomputer	25
Battery	20
Unused space	20
Stimulator assembly	15
Motorola RF/IF strip	15
SRI RF board	5

The power requirement of the wrist unit under various operating conditions is given in Table 4.

Table 4

POWER REQUIREMENTS

Condition	Power (milliwatts)
Microcomputer only	9
RF module only (transmitter turned off)	15
Microcomputer plus RF module (i.e., total steady state power)	24
Total with message stimulator on (24 + 41)	65
Total with transmitter on (24 + 106)	130
Total with alert motor on (24 + 366)	390

VIII SUMMARY AND CONCLUSIONS

The Wrist-Com system concept and hardware/software implementations have been developed during a three-phase project. The work has included the study and adaptation of tactile stimulation methods suitable for this application, development of an on-body FM transmitter, development of a custom-designed hybrid circuit microcomputer and its software, and the development of a centralized control unit. At several stages of the development, test devices and the entire system have been delivered to the Helen Keller National Center for testing and evaluation. In this way, parameter values have been determined and guidelines established for subsequent development steps. The system was demonstrated at the 1978 Interagency Conference on Rehabilitation Engineering, Washington, D.C.

The system's present performance characteristics are satisfactory in many respects; in other respects, improvements are needed. The near-term improvements needed include easing restrictions on certain base-station operating procedures, enhancing parts of the program for the microcomputer, expanding the voltage/temperature operating range of the wrist unit, and reducing the physical size of the wrist unit. Size has been a significant problem since the outset, and considerable progress has been made. However, both near-term and long-term work toward size reduction should be considered in the future. Another improvement that should be considered (before making additional systems) is to design a microcomputer-based base station control unit instead of the current hardwired logic implementation.

It is anticipated that the present implementation of the system will be tested and evaluated at the Helen Keller National Center, Sands Point, New York, and at the San Francisco Rehabilitation Engineering Center, San Francisco, California. These tests should provide a basis for decisions regarding future development.

Appendix

OPERATIONAL CHARACTERISTICS OF THE WRIST-COM SYSTEM

Appendix

OPERATIONAL CHARACTERISTICS OF THE WRIST-COM SYSTEM

A. General

The Wrist-Com base station and on-body unit communicate with each other in half-duplex mode, that is, one-way-at-a-time transmission over a single channel (170.4 MHz). Transmissions can be initiated by the base station operator, by a remotely located switch, and by automatic control from within the base station itself. The events that can occur without operator initiation are: time clock signal, polling for aid request, polling for operational test, aid request alarm, and operational test alarm. Most of the time the system is automatically polling the on-body units looking for an emergency aid request from a user.

Users can be addressed by the base station in three different ways; simultaneously to all on-body units, to a selected group, and individually to each on-body unit. Section C of this Appendix, Format and Meaning of Transmitted Data, describes details of the information transmitted by the base station. The NRZI encoded information is frequency modulated onto the carrier of the base station transmitter. The tone frequencies are 1178 Hz and 1650 Hz. The change from one tone to the other in the middle of the bit cell (Figure A-1 in Section C) denotes a logic one. A steady tone throughout the bit cell denotes a zero. A single transmission is made up of five identical command strings, except for the manual Morse-code mode. Data are transmitted at the rate of 150 bits per second, and a transmission of one packet composed of five command strings takes approximately 0.9 seconds. In the manual Morse code mode, the transmitter stays on for the duration of the message transmission.

The RF transmission from an on-body unit occurs only as a response to interrogation by the base station. The transmission always has the same character, namely, a single 1220-Hz tone that is frequency modulated onto a 170.4-MHz carrier. The modulated carrier is transmitted for 0.5 seconds. The transmission signifies one of three conditions: a request for aid, an acknowledgment of message receipt, or operation of on-body unit is satisfactory. The base station identifies the condition that is applicable by remembering its operating-mode status, and identifies the specific on-body unit transmitting the RF by remembering which unit was addressed.

In the present implementation of the system, certain operating sequences can result in unsatisfactory operation because of conflicts that arise when certain events occur simultaneously. Some (perhaps all) of these conflicts should be resolved before conducting the field tests planned with six on-body units. Some operations will probably still be awkward because half-duplex rather than full-duplex (two frequency channels) is used in this implementation, which has now evolved into a fairly complex system. Three types of conflicts have been identified. One type occurs when commands initiated by the base station operator have near coincidence to independently timed commands, namely, the commands for time clock signal and the operational test signal. A second type of conflict occurs when the independently timed commands (time and op-test) occur in near coincidence. The third type (which sometimes is the source of type one and two conflicts) occurs when an on-body unit is commanded to do two things at the same time, for, example, respond to three push-button switch closures (aid request) and display a tactile code simultaneously. Some of the conflicts can be resolved, at least for the present time, by requiring the operator and user to follow prescribed procedures. Resolution of other conflicts will require hardware/software modifications and/or simplification of the features included in the system.

B. Operating Modes

The system is capable of operating in any one of seven distinct modes; two are automatic polling modes, and five are manual modes. The system is switched from one mode to another on a prioritized basis. Most of the time the system is in the aid request polling mode ready to respond to emergency requests from the on-body unit(s). This polling mode can be interrupted by the operational-test polling mode or any of the manual modes (except when the alarm condition exists, i.e., an aid request has been detected by the base station). The manual modes include the fire alarm and time clock modes, each of which can be operator initiated at the base station control panel.

The manual-mode signals have the following priority, highest priority listed first: fire alarm, time clock, begin manual Morse code, stop, and single-character Morse codes. The fire alarm has the highest priority unconditionally. The time clock has second priority, but it is conditional--the absence of an operational test alarm and aid request is required before the time clock mode can be initiated. This no-alarm condition is a prerequisite for all the manual mode signals except fire alarm.

The following is a summary of the seven operating modes.

1. Fire Alarm Mode

A fire-alarm command string is transmitted at the beginning of this mode and a stop command string is transmitted at the end (actually a packet of five strings for each command). The fire-alarm and stop commands are automatically addressed to all users simultaneously. This mode is initiated by a toggle switch on the front panel; in a permanent installation this circuit would also be connected to the building's fire alarm system. This mode preempts all other operations. In addition to the usual single transmission of five command strings as a packet, the fire alarm packet is retransmitted 13 seconds following the initial transmission, and is repeated subsequently every 26 seconds until the switch is turned to the off position. Returning the switch to the off position causes a stop command packet to be transmitted to all users. When the fire alarm mode is active, a red lamp on the control panel is turned on. The alert stimulator of the on-body unit is repetitively turned on for approximately one-half second and off for one-half second to signal a fire alarm to the user.

2. Time Clock Mode

A time-clock command string is transmitted at the beginning of this mode, and a stop command string is transmitted at the end. The time clock and stop commands are automatically addressed to all users. This mode is initiated by closing the circuit between two jacks mounted on the front panel of the base station control unit. (In subsequent models the jacks will be mounted on the rear panel.) In a permanent installation a remote switch will control this mode. The alert stimulator of the on-body unit vibrates as long as the switch contacts are closed, providing that the closure duration is less than a time-out limit set in the microcomputer. (The above statement is true to a first approximation; there are delays within the base station control unit that causes some variance between the duration of contact closure and duration of vibration period.) When the switch contacts are opened, a stop command is transmitted. If the contacts are closed only momentarily, a stop command is transmitted two seconds after the time clock command is transmitted, so the minimum duration of the alert stimulator vibration is two seconds. The expected duration of contact closure is seven seconds. A panel light (not yet actually installed) indicates to the operator that the switch contacts are closed.

3. Manual Morse Mode

A manual Morse begin (start) command is transmitted at the beginning of this mode, and a stop command is transmitted at the end. This operational mode can be used in any of the three addressing modes, namely, individual, group, or all users. The operator selects the address mode and specific address by means of panel switches. To initiate this mode the operator depresses the switch labeled "Begin"; the command string is transmitted, and a green panel light is turned on for the duration of the transmission. The alert stimulator responds with a message ready signal. This tactile signal consists of two closely spaced vibration periods followed by an off period and two more closely spaced vibration periods. (It takes five seconds to present the message ready signal to the user.) When the system is ready to transmit and receive the operator's keyed input, the green panel light is again turned on (it is off while the message ready signal is presented to the user). Two jacks on the front panel permit a Morse code key to be connected to the system, and the message stimulator vibrates whenever the jacks are shorted together. In this mode of operation the RF carrier remains on continuously, and the manual Morse code is not NRZI encoded. The mode is terminated when the operator depresses the "Stop" switch on the panel. If the operator should fail to push the stop switch, after a delay period (20 seconds) the base station will automatically transmit a stop command and return to a polling mode.

4. Acknowledge Mode

This mode is possible only when the command is addressed to one user (not multiple users). After setting the thumbwheel switches to the desired address and selecting single-address mode, the acknowledge mode is initiated when the operator depresses one of the four green-colored message switches on the panel. Depressing a switch causes a white "busy" light on the panel to be turned on, and the appropriate command string is transmitted. The on-body unit reponds with a message ready signal on the alert stimulator, and the selected Morse code character is presented five times in sequence to the user by the message stimulator. Two rates of Morse code presentation are possible, and the desired one is strap-selected on the microcomputer. For the fast rate a dot has a duration of 0.16 seconds, and a dash has a duration of 0.48 seconds. For the slow rate the durations are 0.25 seconds and 0.75 seconds. The four Morse code characters presently used are: "W," "F," "G," and "X."

When the user receives and understands the Morse code character, the proper action is to depress the push-button switch on the on-body unit one time. This terminates the vibration of the message stimulator and sets an acknowledge flag in the microcomputer. Subsequently the base station will interrogate the on-body unit, and if the flag is set the on-body transmitter is activated to acknowledge receipt of message. If the user does not depress the push-button switch, the transmitter is not activated upon interrogation, and a "no acknowledge" panel light is turned on at the base station to alert the operator. To indicate the absence of acknowledgment, the light will stay on and the base station remains inactive awaiting action by the operator. (The light is turned on only momentarily if the acknowledge transmission is returned to the base station.) The proper action by the operator would normally be to push the black "acknowledge reset" button and either send the message again or contact the individual by other means. The busy light is set to stay on for 30 seconds, and at the end of this period the base station interrogates the on-body unit. This length of time was selected to allow the user to receive the message ready signal and five presentations of the longest Morse code alpha character (Q) at the slow message rate. While the busy light is on, the operator should not interrupt the cycle by closing any of the panel switches except the fire alarm and stop switches (short between time-clock jacks acceptable). Interrupting while the acknowledge mode is in progress aborts the mode, and the acknowledge response is lost. If a second user is addressed in the acknowledge mode while a previous acknowledge mode is in progress, the second message is lost. The stop button can be used as a reset button to abort the mode if the operator makes a procedural error. While the busy light is on the LED address display shows the address of the on-body unit to which the message was sent. If no acknowledge is received, the LED display retains the address until the operator, fire alarm mode or time clock mode intervene. The acknowledge mode is usually terminated by receipt of the acknowledge signal or by closure of the acknowledge reset switch; in either case the system returns to one of the polling modes.

5. Single-Character Mode

In common with the acknowledge mode above, in the single-character mode a single Morse code character is repetitively presented to the user by the message stimulator. There are two distinctions between these two modes. The single-character mode is not used to address a specific user; instead it is used to address all users or a group of users. Secondly, the single-character mode has no acknowledge capability. In preparation for the single-character mode, the operator selects the desired address mode and the specific address. The operator then depresses the appropriate (green-colored push button) message switch to select the code character and initiate transmission of the command string. (There is no stop command required to terminate this mode or the acknowledge mode.) The Morse code characters and the two rates of presentation of the tactile signals are identical in the single-character and acknowledge modes. At the base station the single-character mode is terminated after the approximately one-second duration of the command strings transmission, and the base station returns to a polling mode. The mode terminates at the addressed wrist units when the user depresses the wrist push-button switch, or when the character has been repeated five times.

6. Operational-Test Polling Mode

This mode is initiated on one-half hour intervals from a timing circuit within the base station, and it can also be initiated by the operator from a push-button switch. The mode can be disabled by a toggle switch, and a panel light is turned on to indicate this status. This operational-test (optst) mode has a lower priority than any manual mode and a higher priority than the aid request polling mode. The system will automatically switch from the aid request polling to the optst polling when initiated by the timing circuit or the operator. (Note: The operator should not attempt to force the system into two successive optst polling modes without an intervening operation, such as allowing at least one user to be addressed in the aid request polling mode--otherwise the base station will not respond properly.) The optst is a "go/no-go" type of test. An on-body unit is interrogated by the base station, and if the command string is correctly decoded and acted upon, the on-body transmitter is activated to indicate proper operation. Each on-body unit is addressed in sequence until all units have been polled. The interrogation begins with the highest address. Since there is now only one unit, the address counter in the base station is strapped to count only one. The counter is capable of counting to 255 by strap selection. A feature which is partially included in the current base station permits removing up to four addresses from the active list of addresses to be polled. (Four rather than five addresses was selected for simplicity of implementation even though plans call for six on-body units for field testing. This will mean that during field testing at least two of the six on-body units must be turned on if the optst polling mode is active to prevent a false alarm.)

When an interrogated on-body unit fails to activate its transmitter, an alarm condition is indicated by a red panel light and an audible alarm. (In the present implementation the audible alarm can be disabled by a back panel switch as a convenience during system development and testing.) The only actions to which the base station will respond when in an alarm condition are initiation of the fire alarm mode or operator reset of the optst alarm. The operator is expected to take predetermined emergency action when an optst alarm occurs. The LED address display will indicate the address of the unit that failed to respond until either the mode is terminated, or the addressed unit responds to a subsequent push-button initiated interrogation. When the alarm reset push-button switch is closed, the light and audible alarm are turned off, and optst polling is reinitiated beginning with the address of the on-body unit that caused the alarm. If the on-body unit again fails to respond, the alarm condition is reestablished. When all on-body units on the active list have responded the optst mode is automatically terminated and the aid request polling mode is entered.

A conflict can occur in the current system between the timed initiation of the optst mode and the time clock mode because they are asynchronous. The operator can also cause problems by interrupting in the middle of an optst polling cycle. (This situation needs to be resolved, preferably before field testing with six units.)

7. Aid Request Polling Mode

Most of the time the Wrist-Com system is operating automatically in this mode. In the polling process each on-body unit is interrogated in sequence to determine whether its aid request flag is set. If the flag of the addressed on-body unit is not set, there is no response from that unit and the base station proceeds to interrogate the next-lower numbered address. The number of addresses polled at the present time is six; this number is strap-selectable up to a maximum of 255 (however, it would be impractical to operate the current system with 255 users, as explained below).

In an emergency situation the user closes the push-button switch on the on-body unit three or more times within a five-second time period. (The same switch is used to signal message acknowledged). The successive switch closures set the aid request flag in the microcomputer. When the flag is set and the unit interrogated, the on-body transmitter is activated. The receipt of a transmission by the base station constitutes an alarm condition. As in the optst mode described above, an audible alarm and a red panel light are turned on, and all actions except fire alarm and reset are locked out. The LED address display holds the address of the on-body unit to identify the user requesting aid. When the operator clears the alarm condition at the base station by closing the reset pushbutton switch, the base station transmits an assurance command string to the requesting user, and the base station returns to the polling cycle. The on-body unit responds to the assurance command with a short vibration burst from the alert stimulator to assure the requester that help is on the way.

For a small number of users, perhaps as many as twenty, the present method of sequential aid request polling is satisfactory. However, for large numbers of users it would take an excessive amount of time. At a later point in the development of the system a different polling method is anticipated. In this method there would be two levels of polling, first at the group level and then at the individual level. When a transmission response has been received after a group interrogation, indicating a member of the group is requesting aid, the individual members of that particular group would be polled to identify the requester. If the full capacity of the system (255 users) is implemented, a third level of polling would probably be desirable--groups having a large membership would be subdivided. Other options would also need to be considered at this point in the system development, such as increasing the bit rate of the RF transmission to decrease the on time of the carrier. For present purposes, the group assignments indicated in Table A-1 have been made.

Table A-1

GROUP ASSIGNMENTS

Group Number	Number of Users in Group	Function
1	63	Clients
2	32	Client Reserve
3	64	Staff
4	32	Staff Reserve
5	32	Reserve
6	16	Reserve
7	16	Reserve

C. Format and Meaning of Transmitted Data

Information from the base station is transmitted to the on-body unit by means of a frequency-modulated radio link. The information to be transmitted is encoded in the form of a time-sequential serial stream of binary digits; one complete information unit is called a "command string." Each command string consists of 26 bits, divided into two major parts: The first ten bits are called the "header"; the remaining sixteen bits are called the "text" as illustrated below. The text is further divided into nine bits for "address" and seven bits for "action."

COMMAND STRING

<table>
<tr><td rowspan="2">Header (10 bits)</td><td colspan="2">Text</td></tr>
<tr><td>Address (9 bits)</td><td>Action (7 bits)</td></tr>
</table>

The header is always a succession of nine logical ones followed by a single zero. The on-body unit must receive a properly timed sequence of nine ones and a zero to identify an incoming bit stream as a valid command (additional conditions must also be met). Two "tones" modulate the radio frequency carrier to represent the change in logic state. When the base station commands the on-body unit to perform a function, five command strings are transmitted in sequence. The on-body unit receives and decodes the command strings and tests them to determine whether the address and action bits of two successive strings are identical; if this condition is met, the on-body unit accepts the command as valid and responds accordingly.

The nine address bits are numbered 11 through 19 in the command string, as indicated in Figure A-1. If the address bit A_0 is a zero, the command string is addressed to one particular on-body unit. The bits A_1 through A_8 specify which particular on-body unit is addressed; A_8 is the most significant bit. If A_0 is a one, the command is either addressed to all of the on-body units or to one of the seven possible groups of on-body units. Address bit A_6 determines which of these two options is true--if $A_6 = 1$, then all units are simultaneously addressed; if $A_6 = 0$, then one of the groups is addressed as further specified in the bits A_2, A_3, A_4. (When a group is addressed, the "don't care" bits have the following assignments: $A_1 = 0$, $A_5 = A_7 = A_8 = 1$. These assignments have been selected to avoid a conflict with the header.) In summary:

Address Mode	A_0	A_0
Individual	X	0
All Units	1	1
Group	0	1

Group	A_4	A_4	A_2
1	0	0	1
2	0	1	0
3	0	1	1
4	1	0	0
5	1	0	1
6	1	1	0
7	1	1	1

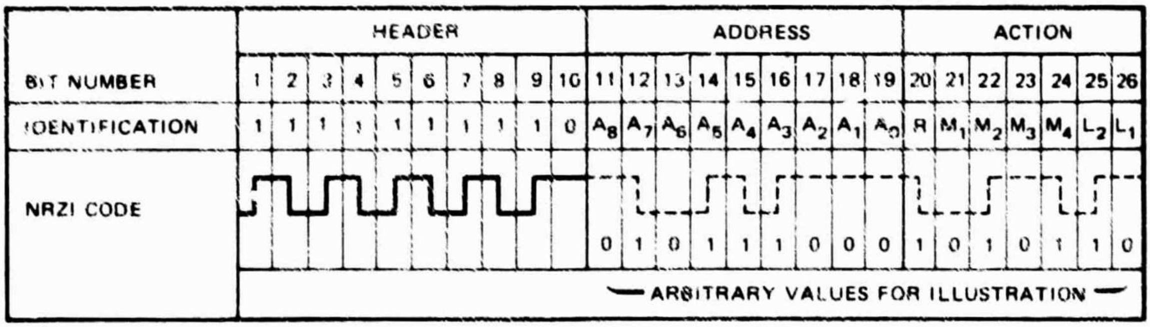


FIGURE A-1 COMMAND STRING BIT ASSIGNMENTS

When the microcomputer in an on-body unit receives and recognizes a command string addressed to it, the action bits are decoded and the required action is performed by the on-body unit. Table A-2 lists the bit assignments in both binary and hexadecimal representations for the various actions required of on-body units.

The action bit labeled R is a one only for those commands that ask for a response transmission from an on-body transmitter; for all other commands, it is zero. In Table A-2, R is shown as a one or zero for the message stimulator codes--it is one if the command string is addressed to an individual on-body unit, because an acknowledge response is expected, and it is zero when addressed to all units or to a group (no acknowledge expected).

The single Morse code character that is presented tactually by the message stimulator is specified by the M_i and L_i bits. Six Morse code characters are shown in the table above--four of which are currently implemented in the base station. (The on-body unit is capable of responding to 26 characters.) Except for the single dot (letter e) and a single dash (letter t) that are given above as special cases, the algorithm for specifying the dot-dash sequence is as follows: The bits L_2 and L_1 are treated as a binary number, with L_2 the most significant bit; this binary number is one less than the sum of the number dots and dashes in a character. In the M bits, a binary one is interpreted as a Morse code dash and a binary zero is interpreted as a Morse code dot. Only the number of dots and dashes given by $(L_2, L_1) + 1$ are recognized as valid in any given character beginning with M_1. For example, in message code number one the number of dots and dashes is $2 + 1 = 3$, and $M_1 = M_2 = M_3 = 1$, so three dashes are specified. $M_4 = 0$ in this example, but this has no meaning to this character since L_2, L_1 limits the information content to the first three M_i.

The encoding method used in the Wrist-Com system is called NRZI (Non-Return-to-Zero Inverted). In this method, a change of state (e.g., from 0 V to 5 V, from 5 V to 0 V, or from a tone of one frequency to tone of another frequency) represents a logical one. A logical zero is represented by the absence of a change in state.

The NRZI code and two other codes are illustrated in Figure A-2. The RZ (Return to Zero) code always returns (or remains) at zero between bit periods. Note that pulses in RZ code have one-half the duration of the shortest NRZI pulse width. This means the RZ code system must have twice the frequency response of NRZI; alternatively (if the required frequency response is to be held the same as for the NRZI), twice as much time is required to transmit a message.

Both the RZ and NRZI codes belong to the non-self-clocking class, which means that timing (clock) information is not inherent in the code. An example of a self-clocking code is the F2F code also shown in the figure. (This code is called frequency-doubling and several other names, including frequency modulation, bi-phase, and Manchester II.) Note that the F2F code has the same upper frequency requirement as the RZ code.

Table A-2

CODE ASSIGNMENTS

Transmit Priority	Action Function	Action Code							Action Code Plus Bit A_0 in Hexadecimal	
		R	M_1	M_2	M_3	M_4	L_2	L_1	Group/All	Individual
1	Fire signal, alert stimulator	0	1	1	0	1	0	0	B4	--
2	Time signal, alert stimulator	0	0	1	0	1	0	0	94	--
3	Start manual Morse mode	0	1	0	0	1	0	0	A4	24
4	Stop	0	0	0	0	1	0	0	84	04
5	Message stimulator code No. 1(G)	1/0	1	1	0	0	1	0	B2	72
6	Message stimulator code No. 2(F)	1/0	0	0	1	0	1	1	8B	4B
7	Message stimulator code No. 3(W)	1/0	0	1	1	0	1	0	9A	5A
8	Message stimulator code No. 4(X)	1/0	1	0	0	1	1	1	A7	67
9A	Polling for aid request	1	0	1	1	1	0	0	--	5C
9A	Send assurance, reset aid flag	0	0	1	1	1	0	0	--	1C
9B	Polling for operational test	1	0	0	1	1	0	0	--	4C
-	Interrogate acknowledge flag	1	1	0	1	1	0	0	--	6C
-	Reset acknowledge flag	0	1	0	1	1	0	0	--	2C
-	Reserved for Morse code dot	1/0	0	1	1	0	0	0	98	58
-	Reserved for Morse code dash	1/0	0	0	1	0	0	0	88	48

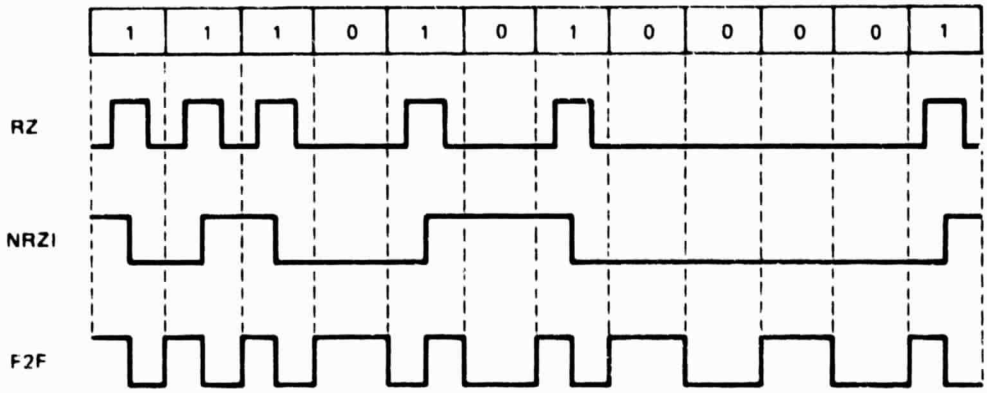


FIGURE A-2 EXAMPLES OF CODE PATTERNS

Many codes are suitable for a system like the Wrist-Com--no particular code is clearly better than others. The NRZI code was chosen in Phase One because it is simple to generate and decode; however, its non-self-clocking characteristics is a disadvantage. This disadvantage was not serious in the hardwired logic implementation used in Phases One and Two, but it has presented some difficulties in the Phase Three software decoding that may require attention.

D. Base Station Controls

The following section identifies the various controls and indicators available to the operator at the base station. Most of the controls and indicators are on the front panel of the base-station control unit, and their placement is shown in Figure A-3. The layout shown is approximately to scale; additional labeling beyond that actually on the panel is included on the sketch. The grouping of the controls and the crowded nature of the entire panel reflects the history of the development of the system--the front panel for the present implementation was used in Phase One and has been added to as the development has progressed.

The symbol for incandescent lamps includes a letter to indicate the color of the lens; "W" means white, "R" means red, and "G" means green. The LEDs used for mode and carrier indicators are green: the LED indicating "power on" is amber. The power switch will be moved to the rear panel in later versions and will require an operator's key to actuate. The jacks for the time input and the manual Morse key will also be moved to the rear panel in later versions. The front panel has a switch labeled "Transmit" that is no longer used and has been disconnected; it is omitted from the sketch.

The sections below list the front panel controls in ten clusters, beginning with controls at the top of the panel.

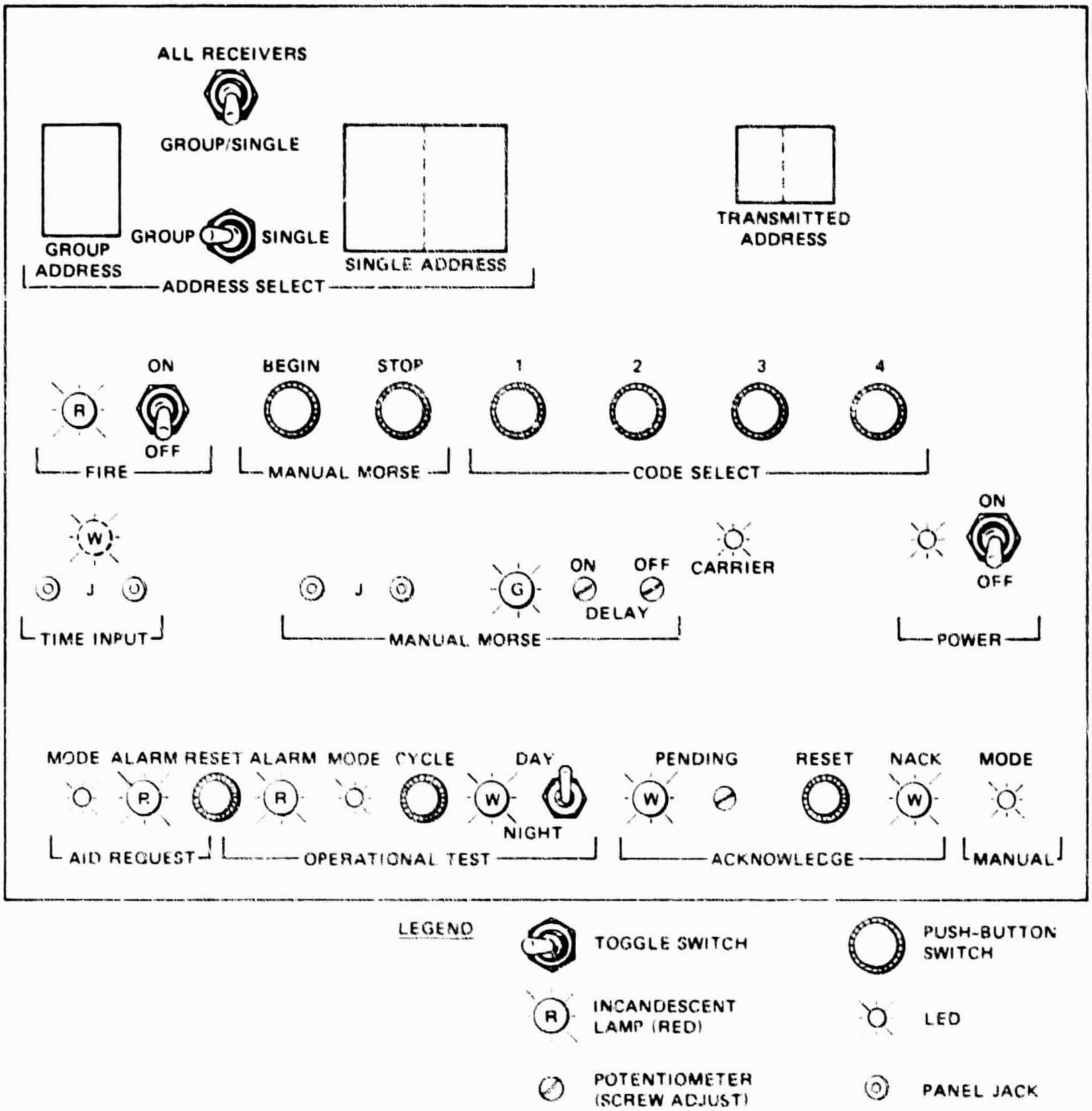


FIGURE A-3 PANEL CONTROLS

1. Address Cluster

The address cluster comprises the "Address Select" switches and the LED numeric display labeled "Transmitted Address." For those operating modes in which the operator selects the destination (address) of the base station transmission, three address modes are possible. With the topmost toggle switch in its up position, all receiving units are simultaneously addressed. This switch position is labeled "All Receivers." (Because the system now has two-way communication with a base station receiver a more appropriate label would be "All Users.") If this switch is down in the "Group/Single" position, then the operator can select either group addressing or addressing to a single individual using another switch, the "Group-Single" switch. The desired group (1 through 7) is selected by the "Group Address" thumbwheel switch. The desired individual address (1 through 255) is selected by the "Single Address" thumbwheel switch. (Note: Numerals 0, 8, and 9 on the "Group Address" switch are not used. The thumbwheel switch for the "Single Address" is satisfactory for the present, but it should be replaced in the next version, because it is cumbersome to select more than fifteen users. This switch is based on the hexadecimal numbering system.)

The numeric LED display is active in all modes of operation. In the current implementation the code number "12" is displayed for group addressed commands and "44" for commands addressed to all receivers. When an individual user has been addressed, the corresponding number (up to 99) is displayed. It is anticipated that in future versions the display will be blanked in group- and all-receivers modes, and an additional digit will be added to accommodate up to 255 addresses. Most of the time this display is sequencing through six numerals (6, 5, 4, 3, 2, 1) while the system is operating in its aid request polling mode.

2. Fire Alarm Cluster

When the "Fire" switch is turned on (up position) all other operations are preempted, and the system is in the fire alarm mode of operation. A red incandescent lamp is turned on to indicate this alarm condition. When the switch is placed into the on position, a packet of fire-alarm command strings is transmitted, and the packet is retransmitted periodically. When the switch is turned off a stop command string is transmitted and the system returns to other pending operations.

3. Manual Morse Control Cluster

There are two parts to this cluster, one on the second line of controls and one on the third. The "Begin" push-button switch initiates the manual Morse code mode, and "Stop" terminates it--the mode is also terminated by an automatic time-out following the last Morse code character transmitted. The panel jacks are provided for connection to an operator's code key. The green incandescent lamp is turned on during transmission of the command-string packet that initiates the mode, and it is turned on again to indicate to the operator that the system will accept keyed input. The delay potentiometers control one-shots in the logic. The "on" delay sets the duration of the period between the initial transmission and the turn-on of the green lamp. The lamp is turned on after two message ready signals have been presented to the user. The duration of this delay at one time needed to be variable, but since this is no longer true later versions will eliminate the potentiometer. The "off" delay determines the interval between transmission of the last manual Morse code character and the automatic transmission of the stop command. This interval is currently set at 20 seconds.

The stop push-button switch, in addition to its primary function in the manual Morse mode, also functions in a manner similar to a system reset.

4. Code Select Cluster

These push-button switches are used to select one of the four Morse code characters that can be transmitted in the acknowledge and single-character modes. Switches one through four correspond to the characters "W," "F," "G," and "X," respectively. Depressing a selected switch causes the appropriate command string to be transmitted to the address selected by means of the address cluster.

5. Time Input Cluster

Two jacks on the panel (located on line three) are provided for connection to an external time clock. Shorting between the jacks initiates the time clock mode, and removing the short terminates the mode. The expected duration of the closure is seven seconds. The dashed-line figure on the sketch indicating a white incandescent lamp shows the approximate location for a lamp that is not yet installed. The lamp will be turned on when the jacks are shorted.

6. Power Cluster

This cluster has three elements, a switch and two LEDs. The toggle switch turns power on to the base station, including the Motorola transceiver (providing that the transceiver switch is also on). While the power is on, the amber colored LED is also on. The green LED labeled "Carrier" on the sketch and labeled "Transmit" on the panel is turned on whenever the RF carrier is being transmitted. (A toggle switch labeled "Transmit," located near the power switch, is no longer used; it is disconnected.)

7. Aid Request Cluster

This cluster consists of two lamps and a push-button switch that is shared with the adjacent cluster. When the system is polling in the aid request mode the LED labeled "Mode" is turned on (it remains on in the event of an aid request alarm). The red incandescant lamp labeled "Alarm" is turned on when an aid request is received. The red push-button switch labeled "Reset" terminates the base station alarm condition for both the aid request mode and the operational test mode, and in the aid request mode it also initiates transmission of the assurance message to the requester.

8. Operational Test Cluster

When the system is polling in the operational test mode the "Mode" LED is turned on. The red incandescent lamp labeled "Alarm" is turned on when an addressed on-body unit fails to respond to an operational test interrogation. The red colored "Reset" push button, shared with the aid request mode, clears the alarm condition. The white push button labeled "Cycle" is used by the operator to initiate an operational test cycle manually. The switch labeled "Day/Night" is used to turn off the operational test mode at nighttime or at other times when the normal complement of on-body units is not turned on. When the operational mode is turned off, i.e., switch in the down (Night) position, the adjacent white incandescent lamp is turned on to alert the operator to this operating status.

9. Acknowledge Cluster

After the acknowledge mode is initiated and its packet of command strings transmitted, the white incandescent lamp labeled "Pending" is turned on. The lamp remains on during the 30-second interval of time between the message character transmission and the time that an acknowledgment should be received. The on-time of this lamp is controlled by the potentiometer adjacent to the lamp. If an acknowledge response is not received by the base station, the white incandescent lamp labeled "NACK" is turned on. The black "Reset" push-button switch is actuated to clear the no-acknowledge condition of the base station.

10. Manual Cluster

The manual "cluster" consists of a single LED (labeled "Mode") that turns on in coincidence with the RF Carrier LED whenever a manual mode transmission occurs.

Miscellaneous--In addition to the front panel controls others are available to the operator. A toggle switch on the rear panel can be used to disable the sonalert. This switch is for convenience and comfort during development and testing of the system. In a subsequent version intended for permanent installation there would be no easily accessible switch of this kind. A fuse is also mounted on the rear panel for the base-station power circuit. The ac power cord and the transceiver control cable emerge from the rear panel.

The Motorola transceiver has one control for power on/off and volume and another control for squelch. A LED on the transceiver is turned on when an RF signal is received, and an incandescent lamp is turned on in coincidence with the transmitter carrier.