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ACQUISITION AND ANALYSIS OF PRIMATE PHYSIOLOGIC DATA FOR THE SPACE SHUTTLE

APL is developing a multichannel data acquisition, telemetry, storage, and analysis system for use with nonhuman primates aboard NASA's space shuttle. The design and prototypes resulting from the current Physiologic Acquisition and Telemetry System Program are expected to lead to the development of spaceflight hardware that will be flown on Spacelab missions tentatively scheduled for 1993. Other potential uses for the system, including Space Station missions, are also being evaluated.

INTRODUCTION

NASA is continually reevaluating its animal physiology experiments with respect to scientific requirements, animal safety, and animal comfort. More powerful and more flexible data acquisition, storage, and analysis systems are needed to gain a better understanding of animal (and thus human) physiology in the microgravity of space. Specifically, NASA is seeking to develop systems to support an international shuttle program of investigative studies with large (>8 kg) nonhuman primates.[1]

Under the sponsorship of NASA/Ames Research Center, Moffett Field, Calif., APL is developing the Physiologic Acquisition and Telemetry System (PATS), a multichannel data acquisition, telemetry, storage, and analysis system for large nonhuman primates. PATS is scheduled for use in the Large Primate Facility, a joint experiment by the United States and France to be flown aboard Spacelab.

The design and prototypes resulting from the current program are expected to lead to the development of spaceflight hardware that will be flown on two missions tentatively scheduled for 1993.

BACKGROUND

The design of the PATS system builds on two decades of experience in developing biomedical devices at APL. The most recent effort directly related to the system is the Programmable Implantable Medication System, a totally implantable device that delivers insulin on a computer-controlled schedule.[2]

Several other biomedical programs closely related to PATS are active at APL. The most recent offshoot of the Programmable Implantable Medication System Program is the Biomedical Implantable Devices Program, which is developing devices that will sample body fluids, such as peritoneal cavity fluid, while simultaneously monitoring various physiologic parameters. The fluids can be analyzed in real time and/or retained in reservoirs in the unit for later analysis. Another part of that effort is the development of biomedical sensors for a variety of parameters, including blood pressure, blood flow, and glucose level.

Other related programs are the Programmable Automatic Shunt System Program, for which an implantable unit is being designed to relieve cerebral spinal fluid pressure in persons suffering from hydrocephalus, and the Biomedical Ingestible Telemetry System Program (see the article by Cutchis et al. elsewhere in this issue), for which an ingestible encapsulated device is being designed and fabricated that will measure and telemeter up to four channels of biomedical data, such as temperature, pH, motility (pressure), and heart rate.

The implantation programs are supported by NASA/Goddard Space Flight Center's Technology Utilization Office. Because the result of the program is flight hardware for space applications, and because it is technically descended from the Programmable Implantable Medication System Program, PATS could be characterized as a "technology transfer in reverse."

SYSTEM REQUIREMENTS

PATS is expected to acquire data from units implanted in the abdominal cavities of rhesus monkeys that will be carried in cages on board the Spacelab. The system must telemeter both stored and real-time internal physiologic measurements to an external Flight Support Station (FSS) computer system. The implanted Data Acquisition and Telemetry Subsystem (DATS) unit must be externally activated, controlled, and reprogrammable from the FSS.[3]

The implanted DATS unit will permit physiologic parameters to be measured on the test animal with minimal physical restraints and will eliminate the need for percutaneous leads that are often the source of infection and discomfort. The system will monitor at least eight channels of biomedical data simultaneously. Physiologic data to be acquired will include temperature, electrocardiogram (ECG), electromyogram, and blood pressure. Heart rate and respiration rate will be derived from the ECG and/or blood pressure waveforms. Other parameters being considered for data acquisition include blood flow and cardiac dimensions.

DATS must contain its own power source so that it can operate for at least one year in vivo to permit prelaunch and post-mission baselines to be established.[3] Mission duration is expected to be between 7 and 10 days.

The design goals for the dimensions of the flight DATS unit are that it be 7.5 cm long, 4.0 cm wide, and 1.2 cm thick; all corners will be rounded to fit more comfortably into the abdominal cavity of an adult rhesus monkey. The case will be made of a titanium alloy and will be hermetically sealed. Stringent reliability and quality assurance requirements for spaceflight hardware must be met. Compliance with animal safety and comfort requirements is being reviewed by the NASA/Ames Research Center Animal Care and Use Committee. Scientific requirements must be translated into engineering requirements, and sensor interfaces must be defined, in collaboration with Ames.

SYSTEM CONFIGURATION

The overall PATS configuration for flight missions is shown in Fig. 1. The DATS unit acquires data from transducers placed in the animal, conditions and digitizes the electronic signals, and transmits the data on request to the FSS within the Spacelab. The ground-based version of the FSS, used for preflight and post-mission activities, is the Ground Support Station.

Linking the DATS with the FSS (or the Ground Support Station) is a command/telemetry link, the APL Biomedical Inductive Link. The FSS will communicate with the shuttle computer system via an interface with one of the shuttle's remote acquisition units.

BREADBOARD SYSTEM

In 1986 and 1987, APL designed, fabricated, and tested a breadboard version of an eight-channel PATS. One breadboard system was delivered to Ames in September 1987; the other was retained at APL. The system design provided the proof of concept required to continue development.

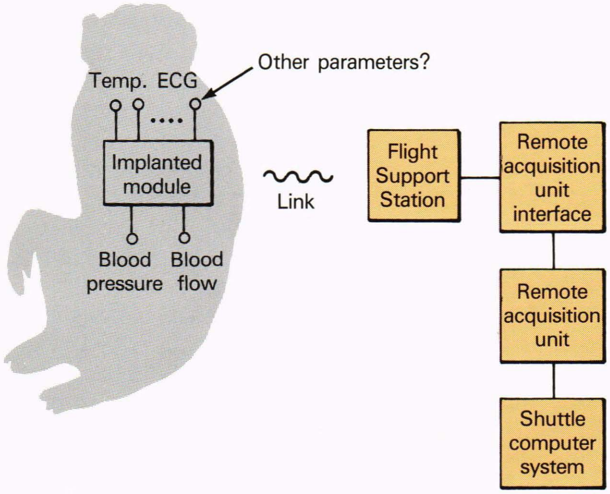

Figure 1—Flight system configuration of the PATS.

The breadboard version of DATS can acquire up to 800 samples per second that can be allocated whenever desired among up to eight input channels. For example, one channel might monitor ECG at 200 samples per second while another samples body temperature at 1 sample per second. (Twelve input channels are available on the breadboard DATS, but a maximum of eight can be active at one time.)

DATS Analog-to-Digital Converter

Figure 2 is a block diagram of the complete DATS unit. Figure 3 is a photograph of the breadboard version, opened to show the circuitry.

The accuracy and resolution associated with each measured parameter are functions of the sensor chosen for use and of the design of the analog-to-digital (A/D) converter in the DATS. The A/D converter in the breadboard system has 8-bit resolution (1 part in 256, or about 0.4%). Signals from the sensors will have to be conditioned to ensure that the dynamic range of 256 steps is optimized for each monitored parameter.

The A/D converter circuitry performs several functions. The control and readout section is the interface with the implanted microprocessor. It connects to the 8-bit random-access memory (RAM) data bus, which provides instructions and reads the data after conversion. A 409.6-kHz clock derived from the microprocessor phase-locked loop is used for timing.

Eight latches control the eight sensor-power switches. The latches are set as desired by the DATS microcomputer. Sensor-power control is separate from the A/D converter itself, and power to any or all sensors may remain on unless the entire DATS is powered off. Separate commands exist for turning power to the channels on and off, and a single command may be used to force all sensor power off.

A negative-voltage DC/DC converter that is used to power a comparator circuit is the primary standby power drain in the A/D unit; it typically requires 40 μA at no load. A precision positive voltage regulator provides the reference for the R/2R ladder network that makes the successive approximations required for the A/D conversion.

The R/2R successive approximation ladder uses 1%-tolerance thin-film resistors in the breadboard system and will be a thin-film network for the miniaturized units that are implanted. The network is specified to be accurate to at least 10 bits, so it should not contribute significantly to system inaccuracies. The output of the R/2R network drives a comparator circuit that determines whether the last bit should be retained or reset to zero. The comparator is fast and is powered only during the conversion interval.

The A/D circuitry receives input via two 8-channel CMOS (complementary-metal-oxide-semiconductor) multiplexers. The first provides normal input from the desired sensors, and the second is a monitor that uses the first three channels for system calibration and battery-voltage monitoring.

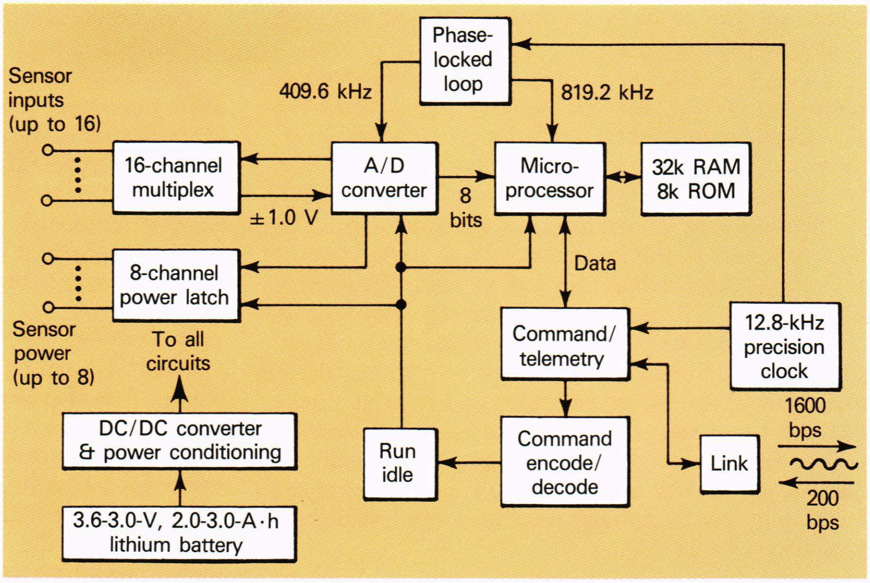

Figure 2—Block diagram of the DATS unit.

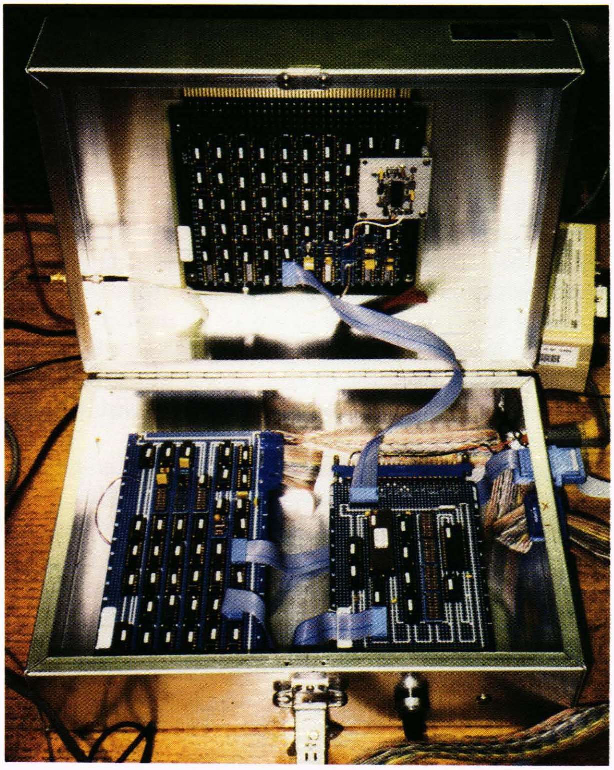

Figure 3—Breadboard version of the DATS unit.

DATS Microprocessor

The DATS microprocessor section consists of a Hitachi HD63701 single-chip microcomputer, a Hitachi HM62256 32-kbyte RAM chip, and some "glue" logic chips. In the breadboard system, this glue logic is implemented by means of discrete CMOS logic. In the flight version, it will be incorporated into a custom gate array to implement the implanted command/telemetry transceiver.

The HD63701 contains an 8-bit microprocessor running an extension of the Motorola 6800 instruction set, 4 kbytes of electrically programmable read-only memory (ROM), 192 bytes of RAM, three 8-bit input/output ports, a multimode timer, and a serial interface. The microprocessor is run at a relatively low clock frequency (approximately 200 kHz) to conserve power.

The microprocessor executes a fixed program resident in the internal programmable ROM. The flexibility of the system is derived from a number of parameters, resident in the internal RAM, that are controlled by the FSS via the command/telemetry link. Sampling protocols and rates are written to the microprocessor, and data are read from the microprocessor via the link.

The A/D converter, described in the previous section, and the 32 kbytes of RAM are available to be connected to the eight-line microprocessor data bus. When the RAM is selected, read/write lines determine whether data are read from or written to RAM on the data bus. When the A/D converter is connected to the data bus, a strobe command writes commands to the A/D converter (e.g., start conversion, turn sensors on/off), and an enable command allows the A/D converter to write data onto the bus.

There are 11 lines between the microprocessor and the internal transceiver. Two provide power (+3.6 V) and ground to the transceiver, five are control or status lines, and two are clock lines—the microprocessor clock and the communications clock. The remaining two carry the microcomputer serial data in (from the transceiver) and serial data out (to the transceiver).

The HD63701 microcomputer clock is designed to operate either with an external crystal or with an external clock input. The latter is used in DATS because the externally applied square-wave clock waveform results in less current drain from the battery than the sine wave generated by an external crystal oscillator. Furthermore, the square-wave clock waveform, which is derived from a phase-locked loop, starts up more quickly.

DATS Transceiver

The command/telemetry link is an inductive link running at about 50 kHz. The data telemetry rate out of DATS is 1600 bits per second (bps). In the flight unit, the DATS command/telemetry coil will be wound around the inside surface of the edge of the titanium case.

The DATS transceiver circuitry performs a number of functions in addition to transferring data out of the implant and receiving commands from the external subsystem. For example, it contains the master 12.8-kHz clock and provides an 819.2-kHz clock for microprocessor operation. The second clock is phase-locked to the 12.8-kHz signal and only operates when the microprocessor is required. The transceiver circuitry also switches the DATS unit off, stopping all operations and reducing the power drain to a few microamperes, whenever the microprocessor runs for 21 min without sending the transceiver a "done" signal and when, in addition, no command has been received from the external unit. This feature is designed to save the battery in the event of a "soft" computer failure such as a noise-induced bit error that results in system hangup.

On the basis of the design goals of the flight DATS unit, a "mass simulator" (Fig. 4) of the planned size, shape, and weight was fabricated using the titanium alloy proposed for the DATS case.

FSS Transceiver

A block diagram of the complete FSS is shown in Fig. 5. Commands are sent from the external FSS transceiver into the DATS unit at 200 bps. The command/telemetry coil for the external transceiver will be placed in a jacket that will be worn by the rhesus monkey.

The FSS transceiver is designed to be powered from a 24-VDC source, in accordance with power availability in the Spacelab. The unit is basically transparent to the FSS and acts similarly to a computer modem.

FSS External Interface

The breadboard system version of the FSS external interface circuitry consists of a parallel input/output card and an RS-232 serial card, each of which plugs into an expansion slot of the FSS computer (discussed below), and an external support circuit that is mounted in a chassis with the FSS transceiver. The parallel input/output and serial cards are commercial peripheral cards designed for the IBM PC AT. The external support circuit was designed at APL.

The external interface circuitry provides control and status lines to the external transceiver. Responding to commands from the FSS computer, the interface circuit controls the state of the external transceiver, for either transmitting or receiving. It receives status data from the DATS and decodes and makes the data available to the computer. It can also be commanded by the FSS computer to generate and transmit to the DATS a special coded-bit sequence that will force the DATS into a very-low-power (sleep) state for long-term storage.

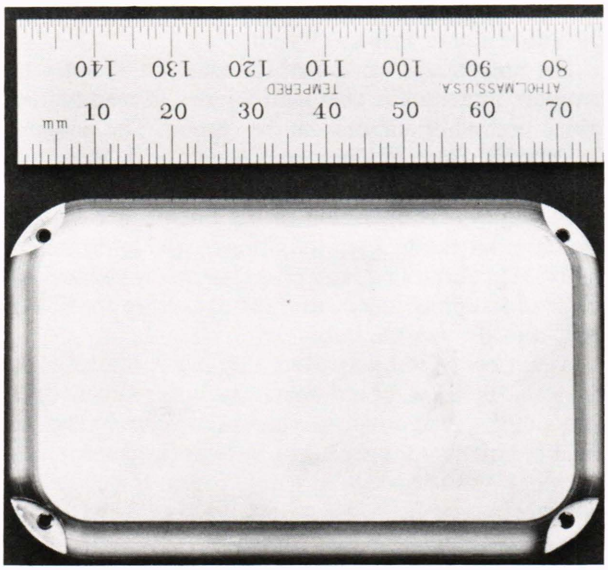

Figure 4—The DATS mass simulator.

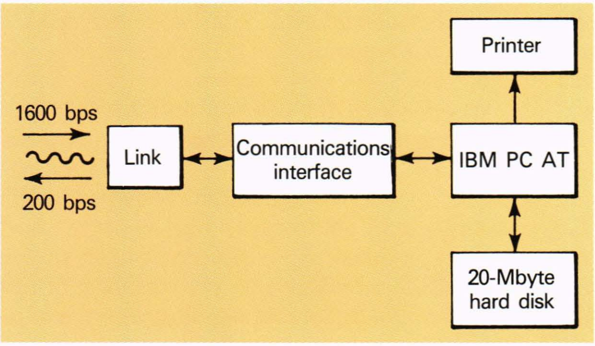

Figure 5—Block diagram of the FSS (and the Ground Support Station).

All data transfers between the FSS computer and the interface circuit are at a single baud rate, 4800 bps. Data are received by the interface circuit from the DATS at 1600 bps and are retransmitted to the computer at 4800 bps. Commands and reprogramming information from the FSS computer are transmitted at 4800 bps, received by the interface circuit, and retransmitted to the DATS at 200 bps.

FSS Computer

The breadboard version of the FSS (and the Ground Support Station) features an IBM PC AT as the central computer. It is expected that either the AT, which has an 80286 microprocessor, or a machine with an 80386 will be used in the final version of the Ground Support Station and for testing, training, and postmission evaluation by the principal investigators.

A flight-qualified version of an 80286 machine probably could be used aboard the shuttle. The CMOS version of the 80286, the 80C286, would probably be incorporated to minimize power consumption. It is also possible that an 80286 board-level computer could be incorporated into a larger machine that would service the entire Large Primate Facility.

The breadboard version of the master FSS software program presents the user with a series of menus from which desired operations can be chosen. The program is compiled from modules written in Quick Basic and Assembly languages.

During typical operation of the breadboard system, the program can be used to configure the interface circuitry, select sampling rates on a channel-by-channel basis, load sampling protocols, read data from the DATS unit, and display the data.

A number of test procedures are incorporated in the program. Some occur automatically during system operation, such as the quadruple handshake during each telemetry link operation. Others, such as the communications link self-test, may be selected from menus by the operator.

SIMULATOR SYSTEM

In order to obtain feedback from the scientists who will be the principal users of the flight version of PATS, a PATS Simulator System (PATS-S), separate and distinct from the breadboard system, has been designed and fabricated. Such a system is needed because the miniaturized and approved flight prototype versions of the DATS unit are not scheduled for delivery until early 1990.

Prior to the commitment of a major effort to miniaturize the DATS circuitry shown in Fig. 3 to the flight package size (7.5 × 4.0 × 1.2 cm), it is highly desirable for the scientists to be able to work with a system whose performance is as much like the eventual flight unit as possible. PATS-S emulates the performance of the planned flight configuration but operates with the hard-wired percutaneous sensors currently being used by the scientists—the sensors are implanted, but the signal is brought outside via percutaneous leads. Up to four channels of sensor data can be connected to PATS-S. The system can be set up and operated in a manner very similar to the planned flight PATS. Four-channel capability was chosen because it is unlikely that any single scientist will use more than four channels of the flight DATS unit.

PATS-S (Fig. 6) consists of an IBM PC/XT/AT (or equivalent) computer, with added hardware and software components. Added hardware consists of a Scientific Solutions, Inc., Lab Tender data-acquisition board that is placed in an expansion slot of the computer and signal conditioning electronics designed and fabricated at APL. The system software provides an interface to the Lab Tender board so that it can be used for various laboratory data acquisition experiments.

PATS-S emulates the data acquisition, storage, and telemetry capabilities of the DATS unit, as well as the communications, control, data-storage, data-display, and data-analysis capabilities of the FSS subsystem. It provides an early indication of the data resolution that can be expected from the implant, well before the implant becomes available, and can therefore be used to evaluate the PATS concept.

The user interface is an important aspect of PATS-S. The system software presents an easy-to-use menu-oriented interface to the data-acquisition and signal-conditioning electronics. Suggestions and comments from users will facilitate improvement of this interface to meet the needs of the scientists who use the flight system. In fact, PATS-S is envisioned as the vehicle for software system development in that software system upgrades and revisions will generally be evaluated on PATS-S before changes are made to PATS.

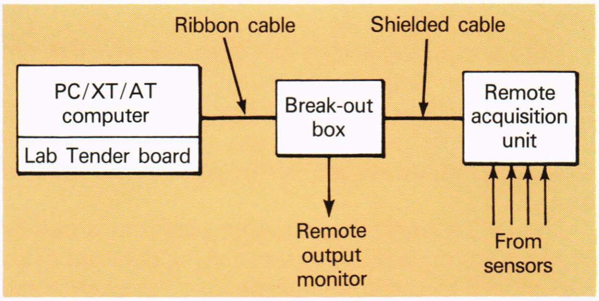

Figure 6—Block diagram of the PATS-S.

In addition to its use in the PATS program, PATS-S is also useful as a general-purpose data-acquisition system for the IBM PC family of computers. Analog data may be captured, displayed, and saved on disk for later analysis. In an 8-MHz PC AT, data may be sampled at rates up to 1000 samples per second on each channel and stored in memory. Data from any channel may be saved on a disk file to free the memory storage for further data capture. Real-time data display is partitioned into three strip-chart windows. Data from up to three channels can be selected for real-time display in one window. In addition, one channel may be selected for an alphanumeric readout that displays data at a maximum rate of once per second. PATS-S can be used in the laboratory, for example, to view one channel each of ECG, blood pressure, and blood flow in the three strip-chart windows. Temperature, which varies relatively slowly, can then be selected for display in the alphanumeric readout.

CURRENT PROGRAM EFFORT

Work is proceeding on the miniaturization (hybridization) of the DATS unit. The volume of the breadboard unit is approximately 13,000 cm^3. The flight design goal for volume is 36 cm^3. By early 1990, the plan is to have a hybridized DATS unit, without the titanium case, that meets the flight-dimension goals as closely as possible. That unit will use commercial parts.

The interface electronics for the Ground Support Station and the FSS is being fabricated on a plug-in peripheral board for the PC AT. The electronics on this board is a simplified version of the electronics performing the same function in the breadboard PATS.

Two upgrades of PATS capabilities are planned for design and implementation. The first is an increase of the total system sampling rate from 800 to 1000 samples per second. The second is the increase of the data telemetry rate out of the DATS unit from 1600 to 2400 bps.

APL is collaborating with engineers and scientists at Ames in the development of a blood-pressure-sensing subsystem suitable for hybridization. The three areas of focus are long-term hermetic packaging, low power consumption, and accurate calibration.

Work is continuing on PATS-S, with attention focused on upgrading the software to enhance the user interface and on expanding the on-screen user help facility.

CONCLUSION

The status of the PATS program presented here is only a snapshot in time of a relatively complex and long-term program. It is possible that the flight configuration of PATS will differ from that currently envisioned.

For example, a subject under discussion as this article goes to press is data acquisition using percutaneous leads. The assumption has been that percutaneous leads would not be used to acquire data in the Large Primate Facility. If a decision is made to use them, the PATS FSS may have to process data from a number of high-data-rate channels connected directly to the computer, in addition to communicating with and obtaining data from the DATS implant. PATS has been designed with a high degree of system flexibility as a primary objective and should be able to accommodate such revisions.

When the shuttle flies with PATS aboard, physiologic data never before available will be obtained and will provide important information on animal physiology in a microgravity environment. It is hoped that this information will make an important contribution to the understanding of human physiology in spaceflight.

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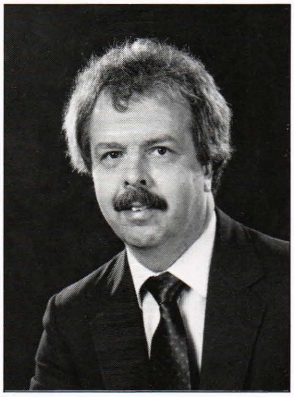

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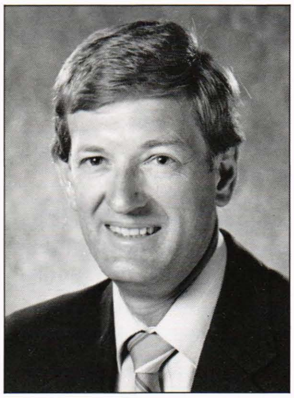

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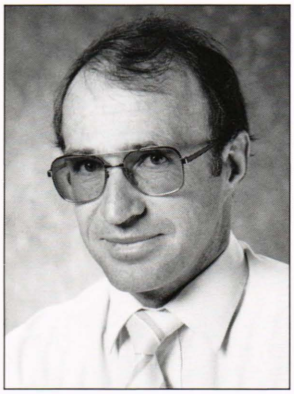

ROY W. DOBBINS has a B.S. degree in electrical engineering from the University of Natal (1970) and an M.S. degree in computer science from the University of South Africa (1978), where he taught courses in operating systems and computer architecture. He is currently a contractor at APL developing software for the Physiologic Acquisition and Telemetry System. Other interests include real-time programming and computer-aided software engineering.