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Solar Powered Hybrid Sensor Module Program

J. M. Johnson and H. K. Holmes

Hughes Aircraft Company
Newport Beach, CA. 92658-8903

Contract NASI—17179
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FINAL REPORT

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Solar Powered Hybrid Sensor Module Program

Final Report

Hughes Aircraft Company

J. Michael Johnson

Solid State Products Division

INTRODUCTION

Geo-orbital systems of the near future will require more sophisticated electronic and electromechanical monitoring and control systems than current satellite systems with an emphasis in the design on the electronic density and autonomy of the subsystem components. Hybrids which have typically served as components in spacecraft electronics will have to assume the role of subsystems and even systems. This report describes results of a project to develop, design, and implement a proof-of-concept sensor system for space applications, with hybrids forming the active subsystem components. The design of the solar powered hybrid sensor modules is discussed and module construction and function is described. These modules combined low power CMOS electronics, GaAs solar cells, a crystal oscillator, standard UART data formatting, and a bidirectional optical data link into a single 1.25 x 1.25 x 0.25 hybrid package which has no need for electrical input or output. Several modules have been built and successfully tested. Applications of such a system for future space missions are also discussed.

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PROJECT OVERVIEW

The problem of providing a data gathering network composed of individual remote sensor modules for use on large delicate structures destined for use in future space construction experiments provided the basis for the conceptual system design. The basic sensor modules had to operate in a stand-alone mode, measure one or more physical parameters and communicate with a central control computer. In addition, they had to be small and lightweight to limit their effect on the vehicle launch weight and on the dynamics of the structure being monitored. A second motivating force which shaped the conceptual design was the desire to limit the complexity of the interconnections used for intranetwork communication and power supply. Discrete wires not only contribute to the overall structure weight, but also pose a problem to deployment since these structures are usually folded or are disassembled during launch and must either be unfolded or assembled once they reach earth orbit. The ideal sensor module would have no electrical connections to the space craft electronics, eliminating the need for the descrete wires altogether. To meet the basic system requirements a self-contained, flexible sensor module was designed which was capable of making measurements of given physical parameters such as temperature, acceleration, or strain, and transmitting this information to a central processing and control unit upon request. The module was fabricated as a single compact unit with its own integral power supply. It was capable of functioning without physical connection to other units utilizing a free space optical data link and it was, at least in concept, able to operate outside of the spacecraft while in orbit.

THE MODULE DESIGN

The sensor module was made up of four general subsystems: (1) the power supply, (2) the data acquisition section, (3) the control section, (4) and the communication section.

The power supply was an array of solar cells attached to the hybrid package. The total power available to drive the hybrid circuitry was limited by incident solar power, the conversion efficiency of the solar cells, and the active area of the solar panel. Gallium Arsenide (GaAs) solar cells exhibited a much higher conversion efficiency and radiation hardness than conventional silicon cells and were, therefore, the best choice for this application.[1,2] Using GaAs cells which typically exibit 16-18% efficiencies, a hybrid with 7 -8cm2 solar cell panel had an operational energy budget of 175-200mW.

The data acquisition section included two primary components: the sensors or transducers and the analog to digital converter, or ADC. Amplifiers and other signal conditioning circuits could have been included to interface the sensors to the ADC if required.

The control section coordinated the functions of the other sections. Its basic function was an on/off switch used to determine when the module was to be active. The control section also provided the hybrid modules with the capability of recognizing the correct request for information codes and coordinated the timing of data transfer to insure data validity. In general, control in a module could have been implemented either as software or hardware. The more control implemented by hardware, the faster the system would be at gathering and processing data. Unfortunately, increasing the hardware also increases the power and usually the substrate area requirements. Using software control requires the establishment of a fairly complex minimum system usually including a microprocessor, and can result in decreased processing speed. In complex control problems, the substitution of software for hardware can reduce the power requirements of the system by multitasking the available hardware. The hybrids developed for this project contained a hardware implementation of the control section.

The communication section was responsible for receiving and transmitting information, and formed the link between the control computer and any remote sensors under its control. The most practical mode of data transmission was serial data over a bidirectional data link due to the minimal energy requirements of serial data transmission as opposed to parallel methods. An optical data link offered the option of operation without wires or cables connecting the data source to the receiver. In addition, the optical data transmission was considered preferable to more conventional RF or microwave transmission systems since it will not interfere with the spacecraft electronics.

While many modulation schemes for transmitting digital data have been described, the method chosen as best suited for this application was Frequency Shift Keying, or FSK.[3] Its selection was prompted by its high noise immunity. Noise immunity was considered an important factor in free space data link since signal to noise levels are normally low. In FSK, digital information is transmitted by modulating a carrier, in this case a pulsing infrared LED, using two distinct modulation frequencies. Data, in the form of a series of 1's and 0's is transmitted by shifting the output signal between the two frequencies corresponding with the digital state. Figure 1 illustrates this principle. Demodulation is simply a matter of deciding which of the two frequencies is present during a given time interval. Error detection and full duplex communication was also implemented over the serial data line allowing for single bit error detection, and simultaneous transmission and reception of data.

THE HYBRID MODULE

Figure 2 shows a block diagram of the sensor module designed for this program. A complete schematic is shown in Figure 3. The combination of the Analog to Digital Converter (ADC) and the Universal Asynchronous Receiver/Transmitter (UART) made up the heart of the system. The ADC and UART had built-in circuitry which functioned as most of the controller section. The ADC, combined with the temperature sensor used in these modules, formed the data acquisition section. The UART, coupled to an FSK decoder, and some I/O conditioning circuits served as the communication section and the power supply was made up of an array of solar cells. The UART was an industry standard CMOS circuit which was designed to handle serial data communication between two digital systems. It's function was to convert 8 bit parallel data bytes, to serial form, adding a start bit, a parity bit, and two stop bits. It also served to transform serial data back into parallel form, checking for parity and framing errors automatically. The data rate was 110 baud and was clocked by a crystal controlled oscillator built into the ADC. The analog to digital conversion was handled by a CMOS 12 bit integrating ADC with an onboard crystal oscillator and separate high and low byte enabling. It was designed to interface directly with 8 bit data bus systems such as the UART and, therefore required little in the way of interfacing circuitry. Data was gathered at 7.5 conversions/second with the 3.58MHz oscillator. Both ADC and UART were monolithic devices manufactured by Intersil. The FSK decoding was accomplished by using a phase-locked loop FSK decoder chip manufactured by EXAR.

Inputs to the modules in the form of a 6-8KHz infrared FSK signal were detected by a pair of infrared photodiodes. This signal was amplified and the low frequency components were removed by two successive high pass filter sections. The FSK signal was decoded by a FSK decoder and the data passed on to the UART. The FSK decoder was programmed to reject signals outside of a 2 KHz window around the 7KHz center frequency. Output information from the module was transmitted on a 9-11KHz optical FSK data link. The technique of shifting the center frequencies of the two data link directions helped decrease noise in the data link caused by optical reflection and internal capacitive coupling. This increased the data transmission distances which were obtained.

The data from the hybrid was transmitted as two 8 bit bytes. The high byte contained 4 bits of data, a polarity bit , an overrange bit, and two filled bits. The low byte contained 8 data bits. A summary of the data link protocols, and data word organization are given in Figure 4.

The modules were designed to recognize a specific request for information code word, or RFI. Until a module received the correct RFI, it remained in a stand-by mode with the output LED disabled. Each module was internally programmed to have a unique RFI with the present system having seven different RFI's. This unique RFI code word enabled the controlling computer to individually access different modules in the same optical field. In this system, the RFI code pair 255, 254 will access any of the seven modules. The RFIs pair 255, 254 should not be used if more than one module is in the OCI field of view since invalid data is likely to occur. The number of unique RFI's could easily be expanded to 127 without requiring a significant change in module accessing protocols since there were 7 bits available for module identification in the input data word.

A test system operation cycle was designed to occur as follows. The controller communication optics were first positioned so that the seven sensors were within range. The controller then polled each of these modules individually to get whatever information each module had available. To do this, the controller first sent out the RFI code for a specific module, for example 1. Reception of this code by module 1 did two things. First, the optical output of the hybrid was enabled and it began transmitting the 11KHz rest carrier signal. Second, the UART module loaded the next valid high order data byte into the transmission register and transmitted it. It should be noted that since only module 1 is actively transmitting a signal, it would be relatively simple to set up a carrier detect system at the controller end allowing verification of module response prior to attempting a data request. After the controller received the first data byte, a request for the second byte was made. The request codes for the first and second data bytes differed by the presence or absence of a 1 in the Least Significant Bit, or LSB, of the code word. After the controller received the second half of the data word it then put the module in a stand-by mode, disabling the output of the module. This was accomplished by either requesting information from another module or by transmitting an ASCII null character. A detailed timing diagram of signals within the module is given in Figure 5. Modules were accessed sequentially or randomly as required. Since the optical data link was an RS232 based FSK system, the computer port for the controller was relatively simple. An artist's representation of modules on a structure in space is presented in Figure 6.

SYSTEM INTERFACING AND OPERATION

Project requirements included the development of a computer controller for the purposes of demonstrating the system. This controller had to be capable of communicating with individual modules using the optical data link. In addition to being capable of initiating contact with an individual module and receiving the returned data words, the demonstration controller had to be capable of displaying this information. A Radio Shack PC-2 pocket computer equipped with a printer and a RS232 port was chosen as the project demonstration controller. In practice, any computer with a RS232 port could have been used. The PC-2 used in this project could store and execute several hundred lines of basic language code. It had the capability of sending and receiving single 8-bit bytes through the RS232 port and the printer could be used if a hardcopy of the data was required. In addition the PC-2 RS232 port was compatable with the communication protocols used including the data rate of 110 BAUD, even parity, two stop bits, and the eight bit byte length. It is important to note that all eight bits of the data and RFI bytes are used. The demonstration controller had to be capable of accessing all eight bits even though ASCII, the code format typically used in conjunction with RS232 data links, is only a seven bit code.

Communication between the controller and individual sensor modules was designed to take place over a RS232 based optical FSK data channel. An optical channel interface, or OCI, was designed and constructed to handle the conversion between the infrared optical FSK signal and the +9V and -9V RS232 required by the PC-2 RS232 port. A schematic of the interface unit is shown in Figure 7.

The OCI transforms RS232 output signals from the computer into the voltage levels and modulates the frequency of the pulsed output LEDs based on digital logic state in a manner analogous to that in the output section of the hybrid sensor modules. The pulsed LED output switches from 6-8KHz. Three LEDs were used to maximize the optical output power of this link. The LEDs were driven by four NiCad batteries built into the OCI and a charging system was provided as part of the demonstration controller. The OCI can be operated while the batteries are being charged but a full charge on the batteries should power the system for several hours of continuous use. The +5V, +9V, -9V, and ground connections required by the OCI were derived from those available in the PC-2 RS232 port. Pins 25, 9, 20 of the RS232 connector were chosen as the +5V, +9V, -9V connections respectively. These three power lines are the only non-standard RS232 electrical connections required by the OCI.

Data words received by the OCI from the sensor modules were first detected by a pair of photo diodes. The signal was amplified by a two stage low noise amplifier and then band limited by a second order band pass filter. The FSK signal was then decoded by a XR2211 FSK decoder as in the hybrid circuit. Finally the signal was transformed into the RS232 compatable +9V and -9V voltage levels and output to the PC-2 RS232 port. The RS232 cable wiring is shown in Figure 8. Pins 4 and 5 were shorted in the OCI so that a correct "ready to send - ready to receive" state was always maintained. The signal output on the OCI was provided to assist in alignment of the OCI and the sensor modules. Monitoring this output with an oscilloscope provided a visual indication of received signal amplitude as well as facilitated the analysis of reflective interference problems.

The basic language program developed for demonstration purposes, shown in Figure 9, had three main sections. The first section was used to establish module ID, and set some offset variables which changed from one module to the next. Module ID was entered by the user in response to a query from the program. The user input module ID, ranging from 1 to 7, was then decoded by the program to establish the appropriate RFI. This portion of the program also prints a header for the hard copy output and sets up the RS232 port for the correct communication protocols.

The second section of the program consist of outputting the RFI's determined in the first part of the program and receiving the return information from the module. The RFI's were transmitted using a "print # - 8 <variable>;" command. This command sends the variable in brackets to the RS232 port. The print H-8 command must be followed by a semi-colon or a carriage return character will also be sent and the data link will be interrupted. Since the RFI's could not be directly translated into ASCII characters, (they use all eight bits unlike standard ASCII which uses only seven), the variable in the "print # - 8" command was a CHR$ XX where XX is the decimal value of the RFI. "CHR$" must be used or the RFI would be translated into ASCII digits.

Data was read into the PC-2 from the RS232 port with the RINKEY$ command. A finite loop was designed into the program to check for reception of a data word. The high order byte was requested and received prior to requesting the low order byte.

The final section of the program assembled the 12 bit data word sent by the sensor module by combining the decimal values of the high and low order data bytes and removing the four unused most significant bits. This section also manipulated the data based on the offset variable established in the first part of the program and determine if the received data is within established limits. Finally the result was displayed.

The program can be run by issuing a RUN command. Using a RUN 500 command bypasses the header generation portion of the program, but still allows the user to input the module ID. The program is an infinite loop once it is started so a BREAK command must be used to stop the program.

SYSTEM COMPONENTS

Solar Cells: The solar cells were (ALGa) As-GaAs cells developed and manufactured by Hughes Research Laboratories, Malibu, CA, 90265. The cells on the hybrid were cut from 2cm x 2cm cells using a diamond saw. Cell efficiencies prior to cutting ranged from 16.0112% to 16.5140%. No attempt was made to determine cell efficiency after cutting. More detail about these cells' structure and capabilities can be found in references 1, 2.

Analog to Digital Converter: A 12 bit CMOS ADC, ICL7109, manufactured by Intersil was used in the hybrid.

Universal Asynchronous Receiver/Transmitter: The UART used was a CMOS UART, IM6403, manufactured by Intersil.

IRLED: The hybrid IRLED used was a SE-1450 GaAs liquid-EPI photoemitter manufactured by Spectronics, Inc., a division of Honeywell.

IR Photodiode: The hybrid IR photodiodes used were SD-1420-2, silicon, planar photodiodes manufactured by Spectronics, Inc. a division of Honeywell.

FSK Decoder: A monolithic FSK decoder, XR2211, manufactured by EXAR was used in both the hybrid and the OCI.

Operational Amplifier: A LM324 quad OP amp was used. This chip was used as the high pass filter/amplifier on the hybrid optical input.

CMOS Schmitt Trigger Inverter: A CMOS hex Schmitt trigger inverter, 54C14, was used in the local oscillators and as digital inverters for various data lines.

CMOS Quad 3-Input and: A 4073B quad 3-input AND gate was used in various places in the circuit.

Quartz Crystal: A standard to sweep back oscillator crystal 3.5795 MHz was used.

Demonstration Controller: This is composed of the optical communication interface, OCI, and the Radio Shack PC-2. The OCI is discussed in more detail in the System Interface Section and more detail on the PC-2 can be found in the PC-2 manuals supplied as part of the contract deliverables.

PACKAGING

The hybrid modules consisted of a two sided, thick film substrate with a Kovar ring frame attached to one side and the solar cells attached to the other side. The hybrid electronics were assembled within the cavity formed by the ring frame. The thick film substrate which formed the package base was a two sided multilayer structure with four gold metallization layers on the circuit side and one on the other side. Metallized vias through the ceramic substrate were used to make electrical connections between the two sides of the substrate. The single metallized layer on the backside was used for solar cell attachment and interconnection, while the four layer side supported and interconnected the circuit elements. ICs, chip resistors, and chip capacitors were attached using conductive epoxy and were wire bonded with 1 mil gold wire. The 400 mil diameter crystal was mounted in one corner of the substrate with three mounting clips which suspended it about 40 mils above the substrate. This allowed the crystal to oscillate, while still providing it with fairly rugged mechanical support.

The infrared LED and photodiodes were purchased in hermetic pigtail style packages. These components were soldered into holes in the ring frame so the lenses faced in the direction of the data link. The pigtail leads were formed down and connected to the appropriate contacts on the substrate. The ring frame was used as the ground contact. Following assembly and test the packages were sealed with Kovar lids. While the prototype hybrids were not hermetic, they could have been made hermetic by substituting sealing glass or solder for the epoxy used to attach the ringframe, filling the substrate vias with solder or glass, and seam sealing the lid.

The final step in assembly was the attachment and interconnection of the solar cells. The solar cell array was composed of 14 solar cells in three different size groups, which were interconnected to produce three separate voltages, +5V, +2V, and -5V. The size of the cells in each of the three voltage sections was different so that the surface area of the array, and hence the current levels produced by each section, could be allocated as required among the three voltage supplies. The cells were mounted on the substrate with conductive epoxy to reduce the back contact resistance and the cells were interconnected by a solder attached, .002 X .040 copper ribbon. A schematic representation of a portion of the hybrid shown in cross section is shown in Figure 10. Although these cells required no covering, a glass plate could have been bonded to the cells with a suitable adhesive to protect them from mechanical damage.

PROTOTYPE HYBRIDS

Six operational prototype hybrids were manufactured and successfully tested; three of these were tested with solar cells. Figure 11 is a photograph of the hybrid module showing both sides. The Kovar lid was removed to make the electronic components visible. The photograph in Figure 12 shows the optical I/O portion of the hybrid in more detail. The crystal, mounted on posts, can be seen toward the back of the hybrid cavity. Transmission distances of two meters have been obtained with the solar powered versions. The effective transmission distance was limited primarily by the relatively low output power of the hybrid LED with respect to the ambient light levels and by reflected infrared signals from the controller output stage. The total optical output power was somewhat less than 0.23 W in a 10° beam. In practice, transmission distances could be increased tenfold by using higher output laser diodes. Other techniques such as optical concentraters at the receiving end, feedback control of the photodiode sensitivities or increased photodiode surface area, would also increase the transmission distances. In the present system, the controller to hybrid data link was limited only by the output power of the controller IRLEDs.

APPLICATIONS

There are several applications for a system similar to the one described. The first is the data gathering network on which this work was based. In this application, each module monitors one or more physical parameters, reporting data to the controller upon request. This concept could be expanded by increasing the internal processing ability of the individual modules and adding some non-volatile memory. A module so equipped could monitor several variables without inputs from the controller. This information could be stored in the onboard memory and transmitted to the controller in a block whenever the controller required inputs from the modules.

An extension of this scheme would be to design smart modules; modules with onboard microprocessors. A given module could then monitor and process the information from its associated sensors. The controller would receive only the end result of the processing and would not have to spend time analyzing the raw data. This type of module could even be programmed to initiate contact with the controller if it detected a condition which warranted immediate attention.

All of these systems are based on a star network design as shown in Figure 13. In a star network, all of the elements of the system communicate with a central controller only, and not with each other. A system of modules could be developed which would communicate among themselves as well as with a controller. More specifically, a module with some processing and control capability could be developed which could transmit and receive information in two or more directions. These modules would act as local control systems and as relay points on a long segmented serial bus network. This type of bus organization is illustrated in Figure 14. If the main controller required information from an area out along the chain, it would send a message requesting this information. The message would be received and passed along by each successive link in the chain until the appropriate control point was reached. The information requested would then be gathered from the peripheral sensor modules and passed back along the chain to the controller. This scheme can be expanded in a manner similar to the star configuration. In addition to the segmented serial bus system, a relay ring structure depicted in Figure 15 could be designed where each module transmitted in only one direction. In this system, there is less of a chance for intermodule interference. Multiple sensors could also be multiplexed onto a single sensor module as shown in Figure 16. A module could also be designed to control mechanical functions on the spacecraft.

CONCLUSION

Three self-contained solar powered hybrid sensor modules were built and tested. They met the project goals of minimal module weight and no electrical interconnections. The project proved the feasibility of designing a complete hybrid sensor module which could perform the required data gathering and communication functions and still be able to function on the power output of an integral solar power supply. For the most part, standard fabrication processes were used. When non-standard techniques were required, the developed techniques were compatible with standard hybrid processing. The use of a free space optical data link between a hybrid and a controlling computer has been demonstrated and methods for improving this link have been identified. Finally, a hybrid module which functioned in a large part as a separate system has been designed and built. While much work remains to be done to produce an actual working system for space applications, the initial results seem very promising and there seem to be many applications of such a system.

ACKNOWLEDGMENTS

The Author would like to express special thanks to John Fackeldey for his contributions to the design and testing of the modules and demonstration system and to Judi Christensen for her expert assembly skills and patience. Without their help, this project may never have been completed.

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2. R. Lou, G. S. Kamath, and R. C. Knechtli, "Radiation Damage in GaAs Solar Cells", 14th Photo Voltaic Speciallists Conference 1980, pg. 1090.

3. H. Taub and D. Schilling, <u>Principles of Communication Systems</u>, McGraw-Hill Inc., pp. 227-228 - FSK Operation and pp. 381-383 - FSK Noise.

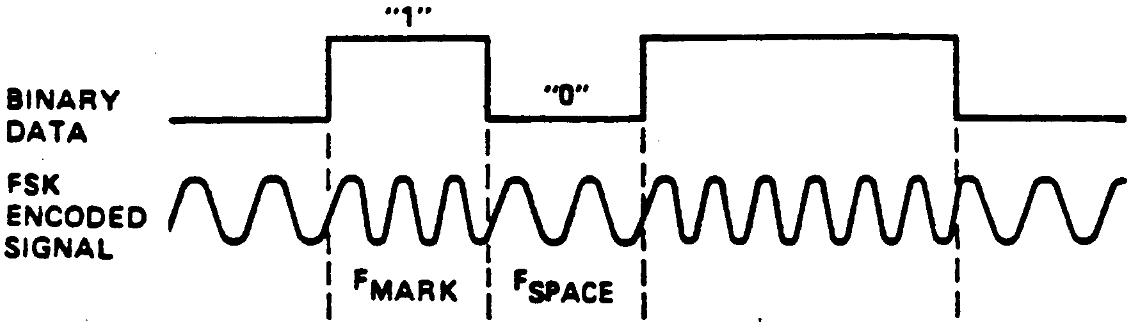

FIGURE 1: FSK DATA TECHNIQUE SHOWNING CORRESPONDENCE BETWEEN FREQUENCY AND DATA STATE.

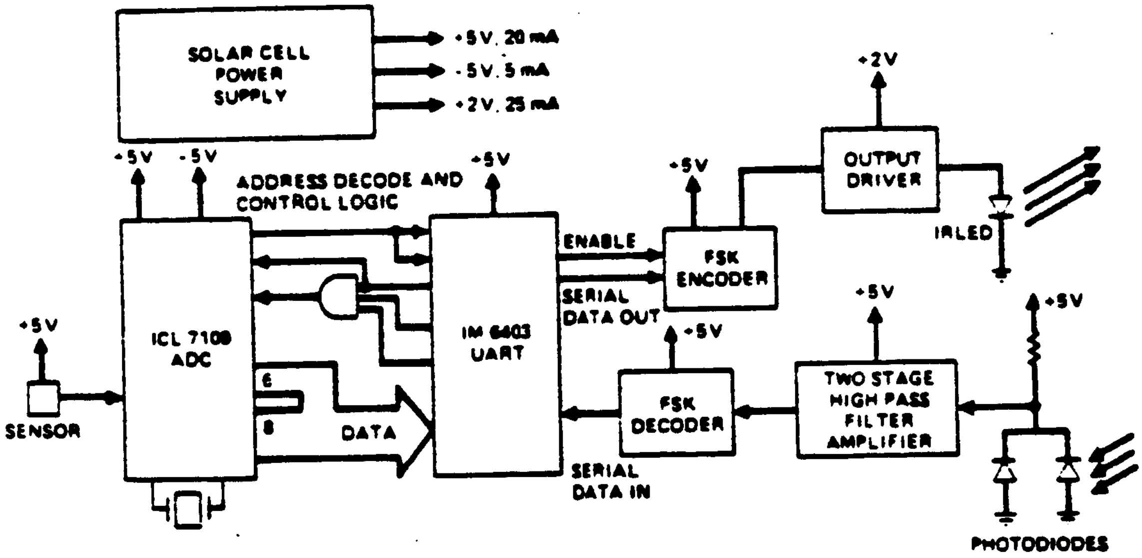

FIGURE 2: BLOCK DIAGRAM OF HYBRID MODULE.

NOTE: V+, V-, GND & VD ARE SUPPLIED THROUGH VIAS FROM THE BACK SIDE OF THE SUBSTRATE

①②③ CORRESPONDING CONNECTIONS TO BE MADE ON EACH SERIAL NO.1, NO.2, NO.3 SHOULD BE SELECTABLE BY WIRE BONDING

R8, R12, R13, R29, R30 ARE ACTIVE TRIM

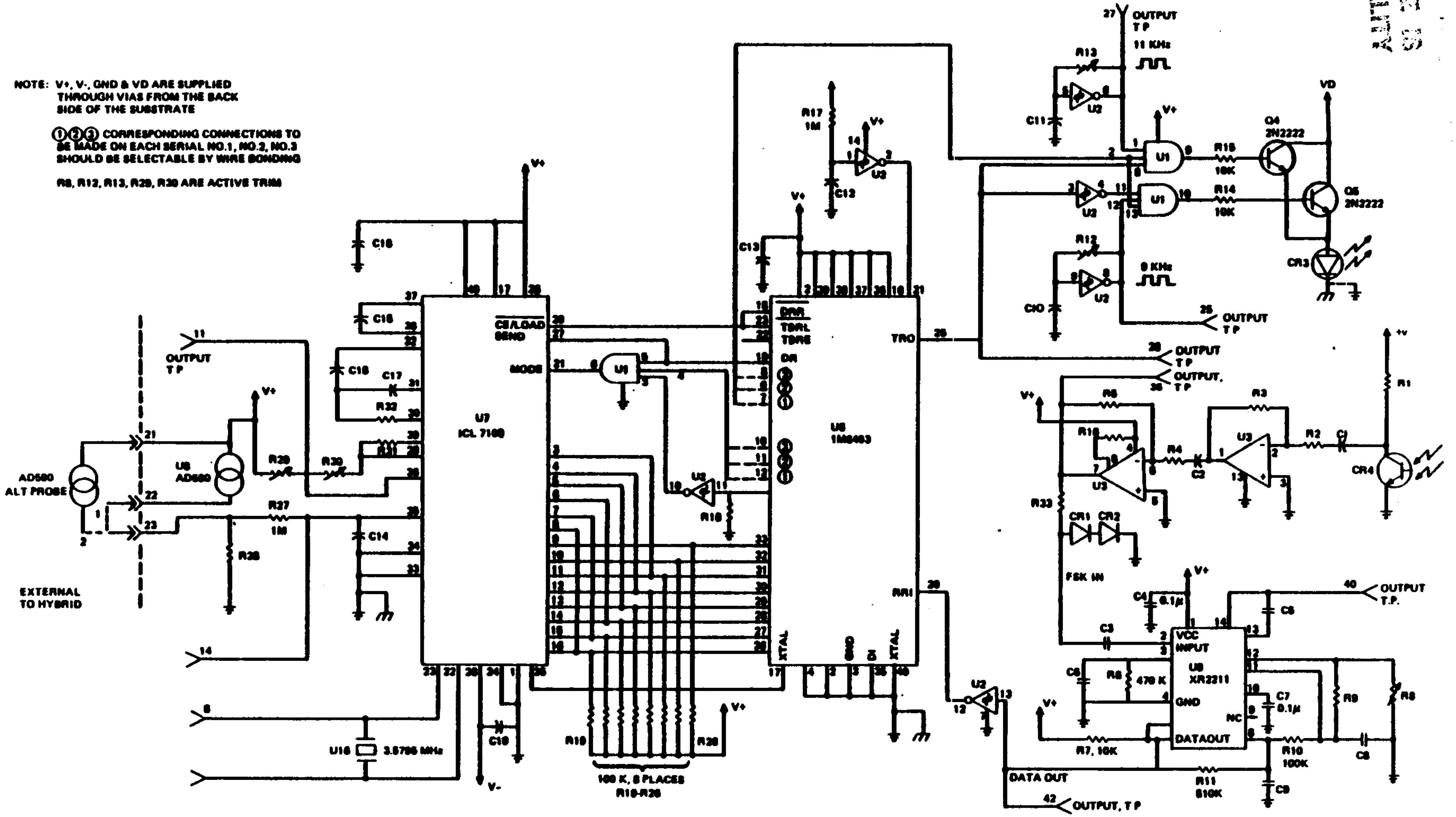

Figure 3. Schematic of the Solar Powered Hybrid.

DATA WORD ORGANIZATION

HIGH-BYTE

1	1	POL	OR	B12	B11	B10	B9

LOW-BYTE

B8	B7	B6	B5	B4	B3	B2	B1

MODULE RFI:

	DECIMAL CODE	
MODULE ID	HIGH-BYTE RFI	LOW-BYTE RFI
1	129	128
2	65	64
3	33	32
4	17	16
5	9	8
6	5	4
7	3	2
ALL	255	254

COMMUNICATION PROTOCOL

WORD LENGTH :	8 BITS
DATA RATE :	110 BAUD
PARITY :	EVEN
STOP BITS :	TWO

WORD PROTOCOL

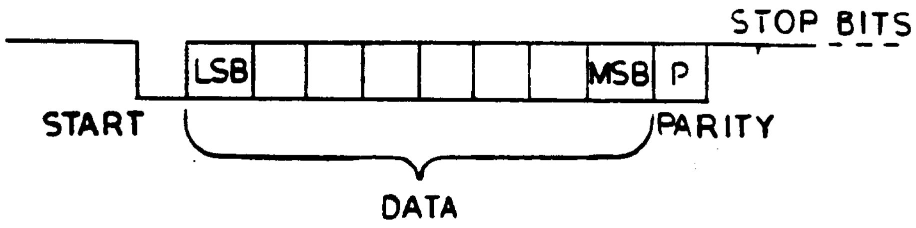

FIGURE 4: COMMUNICATION PROTOCOLS AND DATA WORD ORGANIZATION.

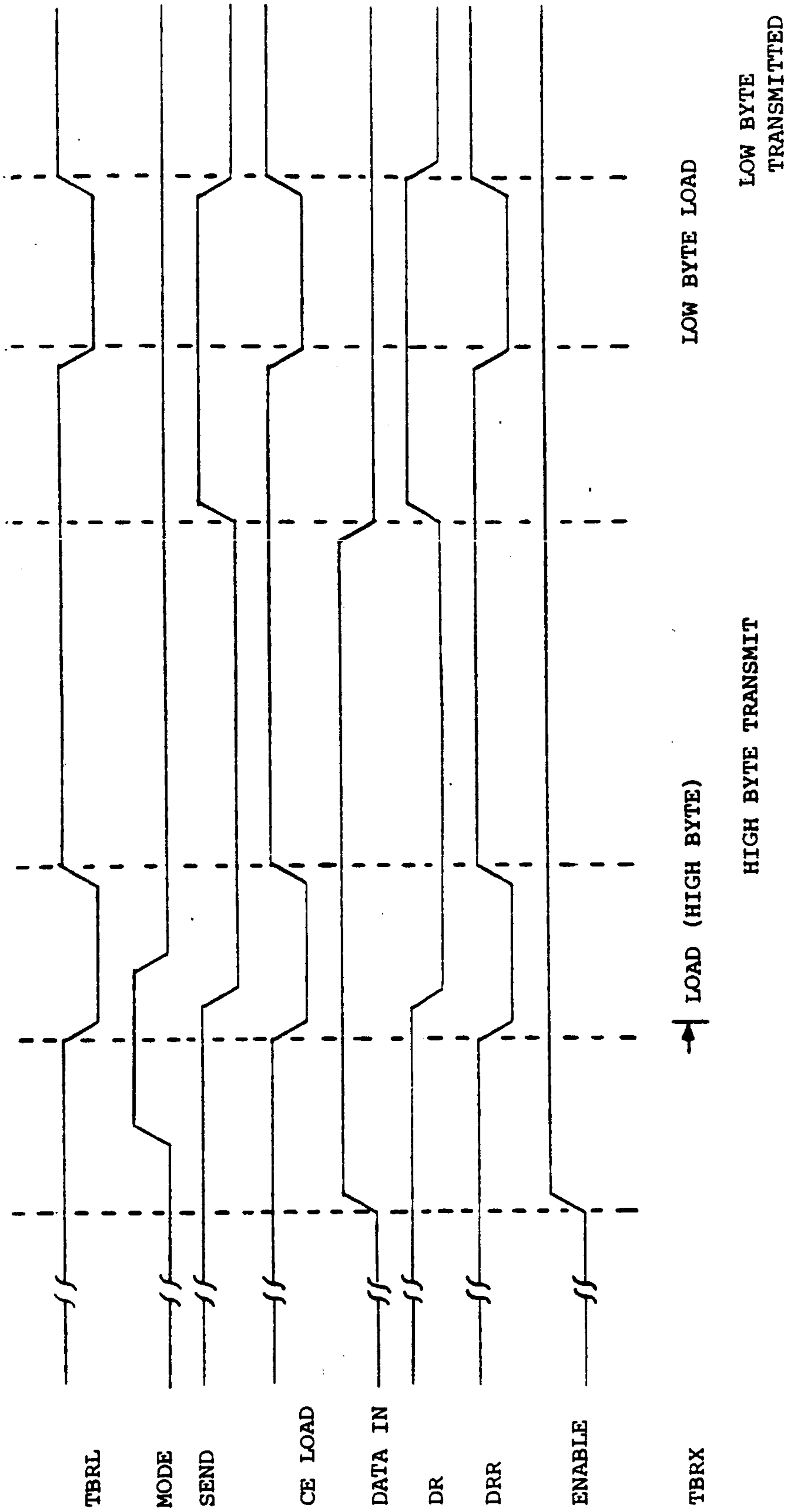

FIGURE 5: TIMING DIAGRAM.

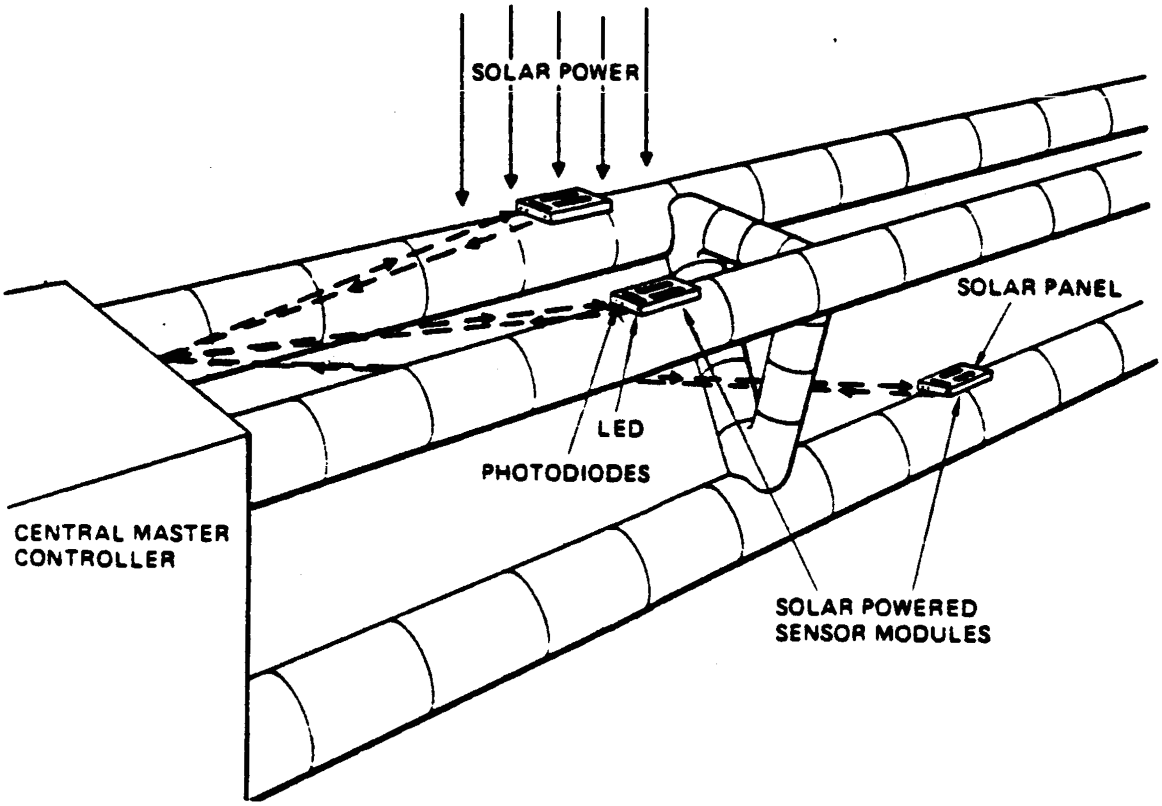

FIGURE 6: ARTISTS' CONCEPTION OF MODULES IN PLACE ON A SECTION OF A SPACE STATION.

ORIGINAL PAGE IS
OF POOR QUALITY

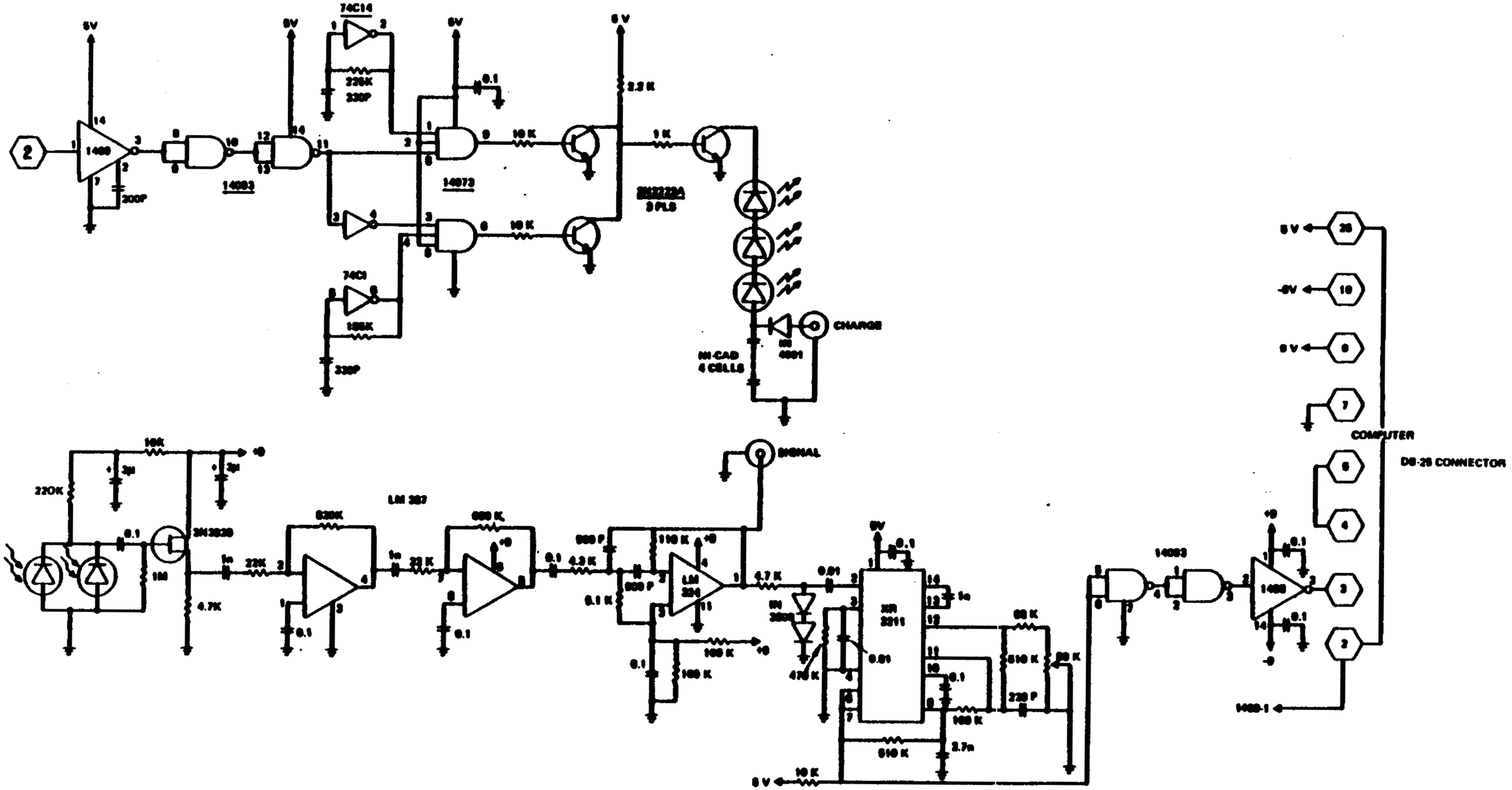

Figure 7. Schematic of the Optical Interface Unit.

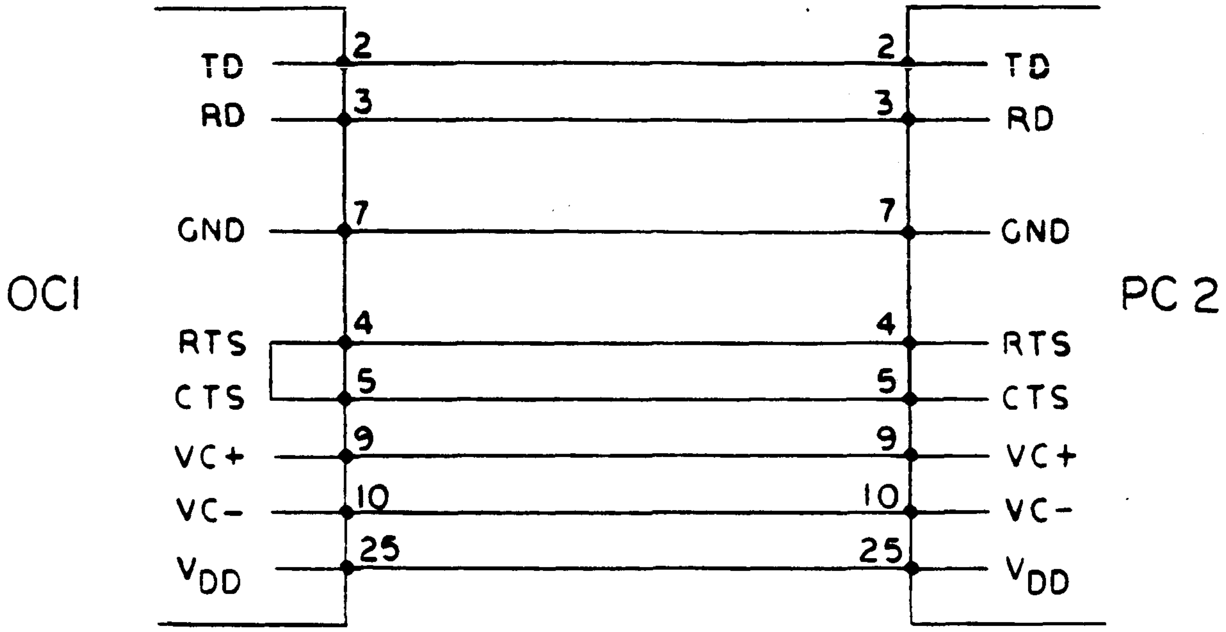

FIGURE 8: RS232 CABLE WIRING.

REPRESENTATIVE PROGRAM

```
500     "C" WAIT 5
510     SETCOM110,8,E,2
520     INPUT "MODULE ID   ":ID
525     IF ID = 2 THEN LET PSO = 64: LET TARE = 100.00 LET SCALE = 1000: GOTO 560
530     IF ID = 3 THEN LET PSO = 32: LET TARE = - 565.0 LET SCALE = 1000: GOTO 560
535     IF ID = 4 THEN LET PSO = 16: LET TARE = 000.0 LET SCALE = .001: GOTO 560
540     IF ID = 5 THEN LET PSO = 8: LET TARE = 000.9 LET SCALE = .001: GOTO 560
545     IF ID = 6 THEN LET PSO = 4: LET TARE = 134.2 LET SCALE = 1000: GOTO 560
550     IF ID = 7 THEN LET PSO = 2: LET TARE = 2526 LET SCALE = 10: GOTO 560
555     PRINT "INVALID NUMBER":PAUSE: GOTO 520
560     INPUT "DO YOU WANT A PRINTOUT? ":ANS$:COLOR 2:LF1
565     IN ANS$ = "Y" THEN LPRINT :LPRINT "MODULE DATA:"COLOR 0
570     OUTST AT 0
575     PRINT # - 8, CHR$ 0:
580     PRINT # - 8, CHR$ 0:
585     PRINT # - 8, CHR$ PSO:
587     PRINT # - 8, CHR$ PSO:
590     PAUSE
595     PRINT # - 8, CHR$ (PSO + 1):
600     FOR I = 1 TO 5
610     B$ = RINKEYS: IF BS <   > "" THEN 635
620     PAUSE
630     NEXT I
635     PRINT # -8, CHR$ PSO:
640     FOR J = 1 TO 5
650     A$ = RINKEYS: IF AS <   > " " THEN 670
660     NEXT J
670     PRINT # - 8, CHR$ PSO:
750     REM PRINT ASC B$: ASC A$:I:J
760     TEMP = ((( ASC B$ -224) * 256 + ASC A$) - TARE) / SCALE
770     REM       IF TEMP <(-10) THEN 585
780     REM       IF TEMP >  50 THEN 585
790     PRINT "MODULE ":ID:"TEMP:" *"
800     IF ANS$ = "Y" THEN LPRINT "MODULE ":ID:" =":ID
805     PRINT "MODULE ":ID:" ="TEMP
810     GOTO 595
850     END
```

FIGURE 9: BASIC LANGUAGE PROGRAM.

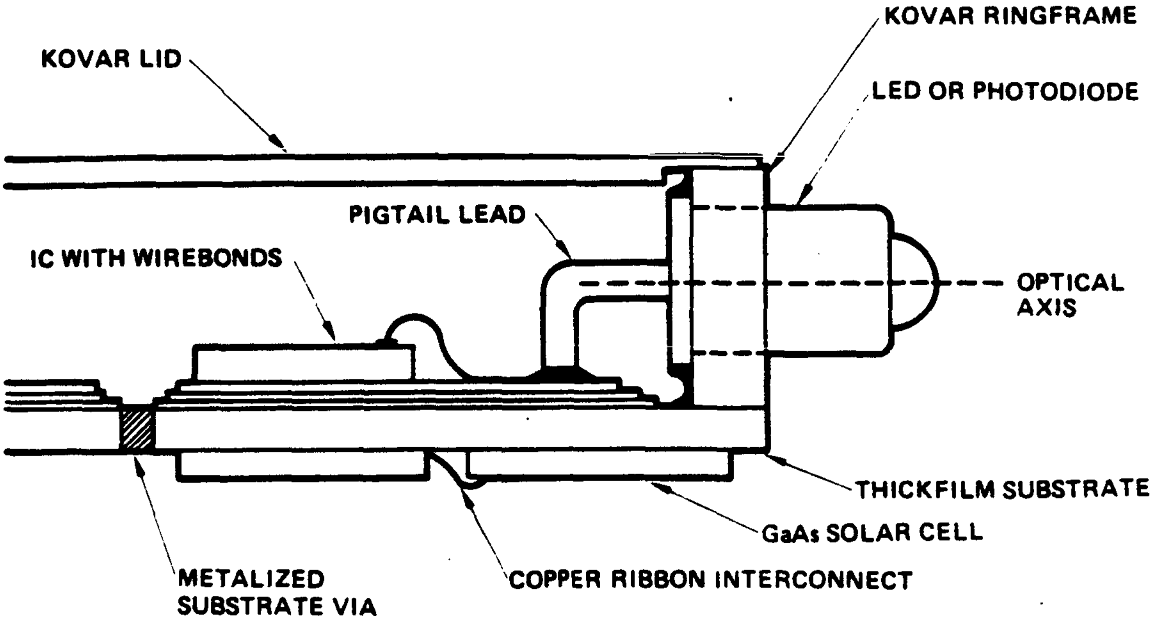

FIGURE 10: HYBRID PACKAGE STRUCTURE.

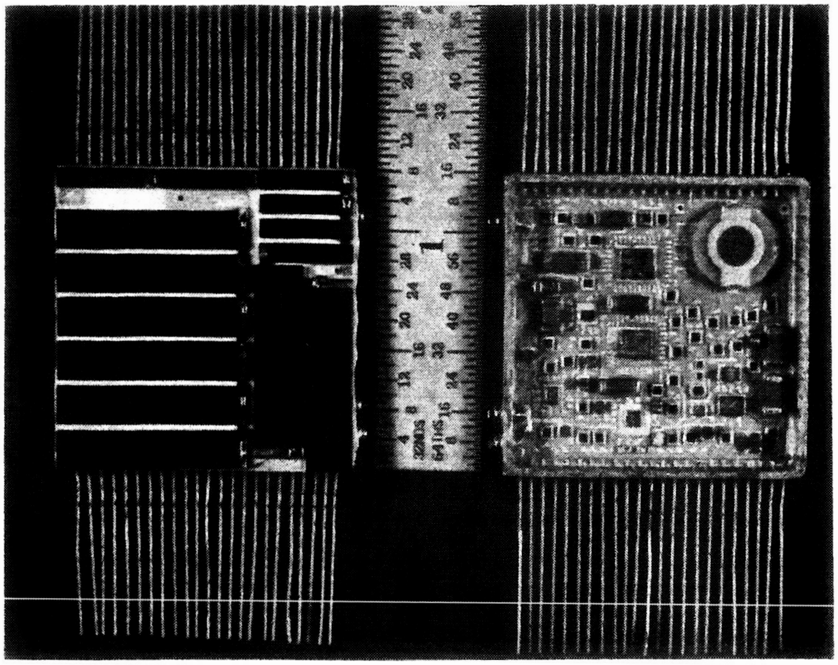

FIGURE 11: PHOTOGRAPH SHOWING BOTH SIDES OF THE SOLAR POWERED HYBRID.

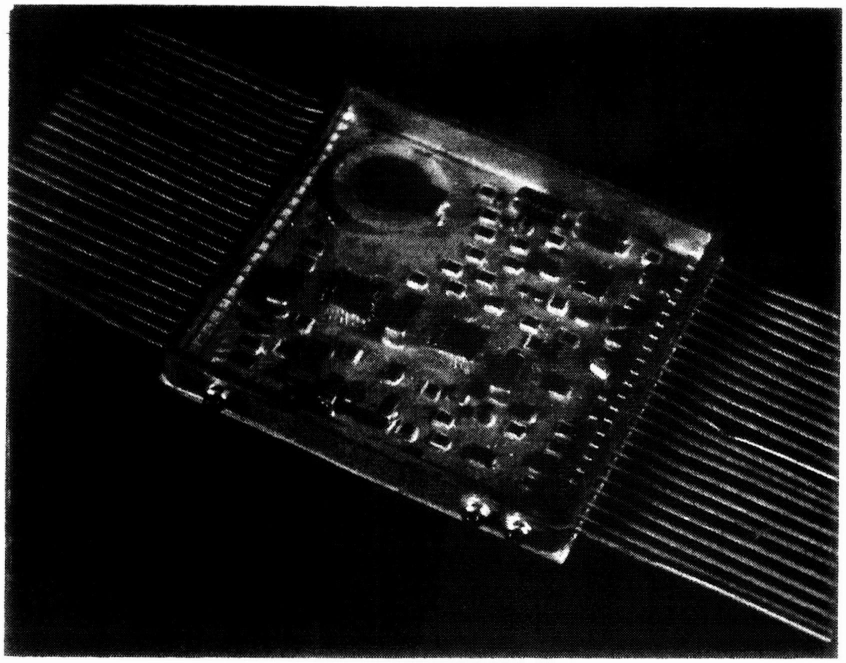

FIGURE 12: CLOSE-UP OF THE I/O SECTION OF A HYBRID MODULE. THE TWO PHOTODIODES ARE ON THE RIGHT AND THE LED IS TO THE LEFT.

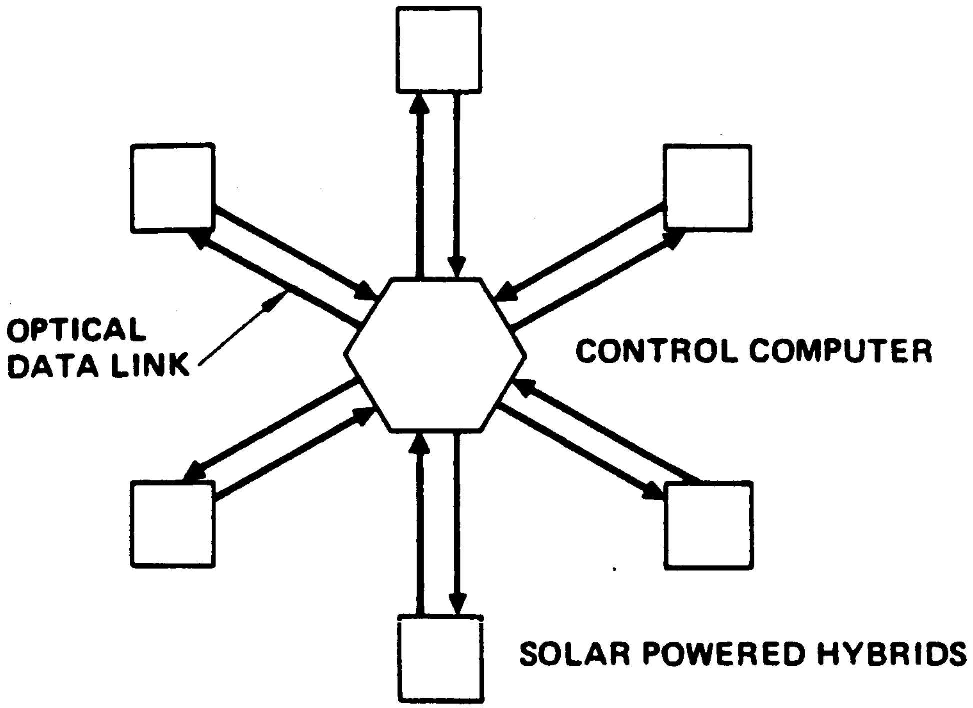

FIGURE 13: STAR NETWORK CONFIGURATION.

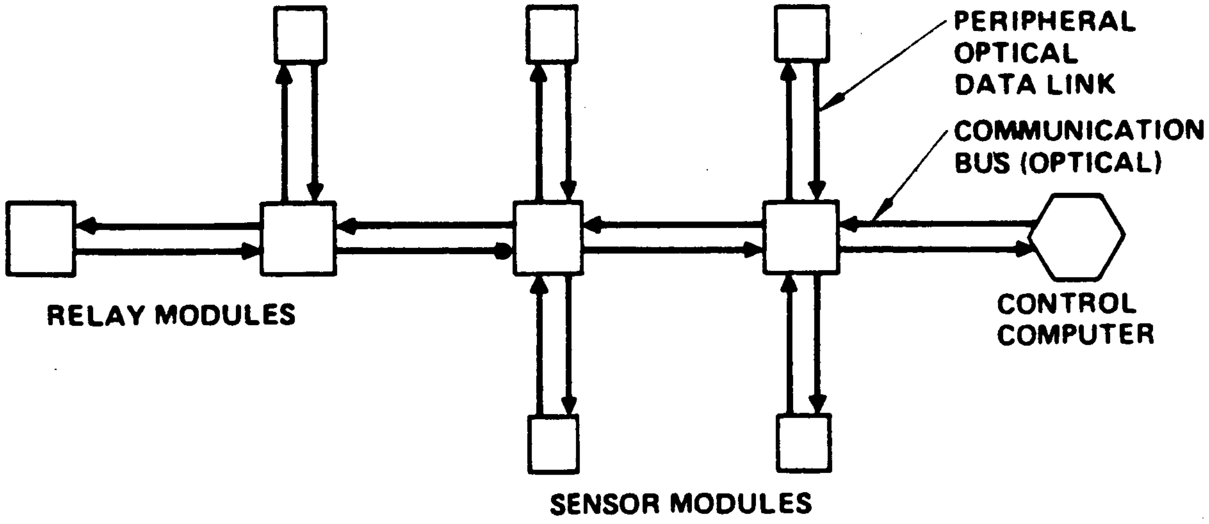

FIGURE 14: SEGMENTED SERIAL BUS NETWORK.

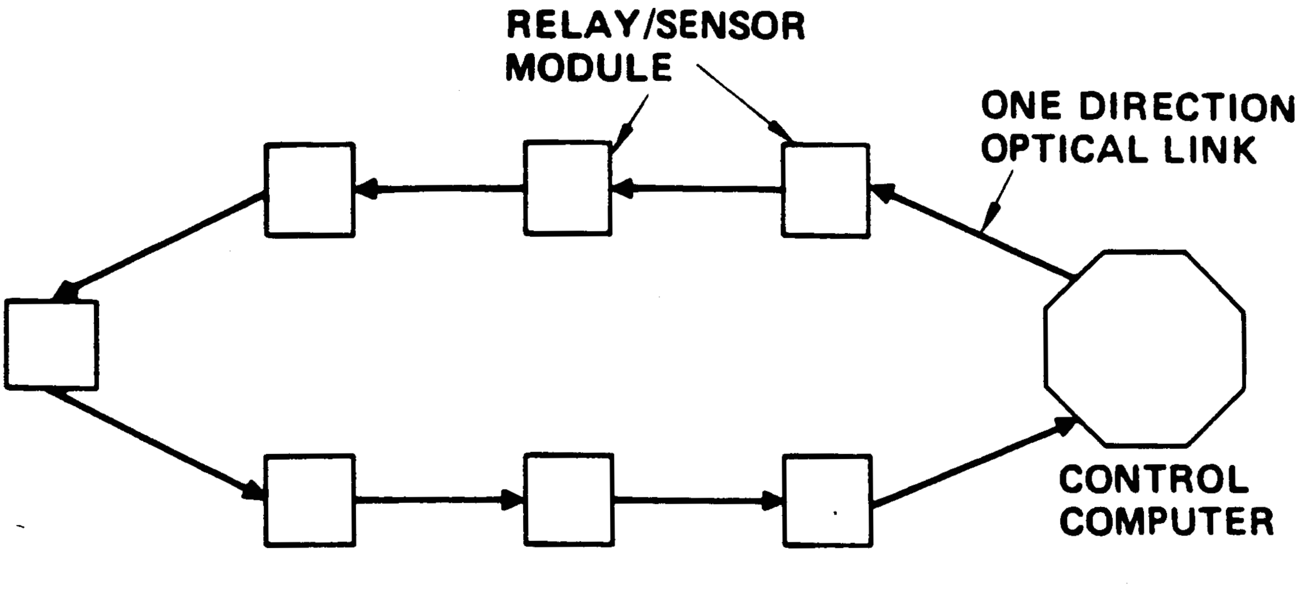

FIGURE 15: RELAY RING CONFIGURATION.

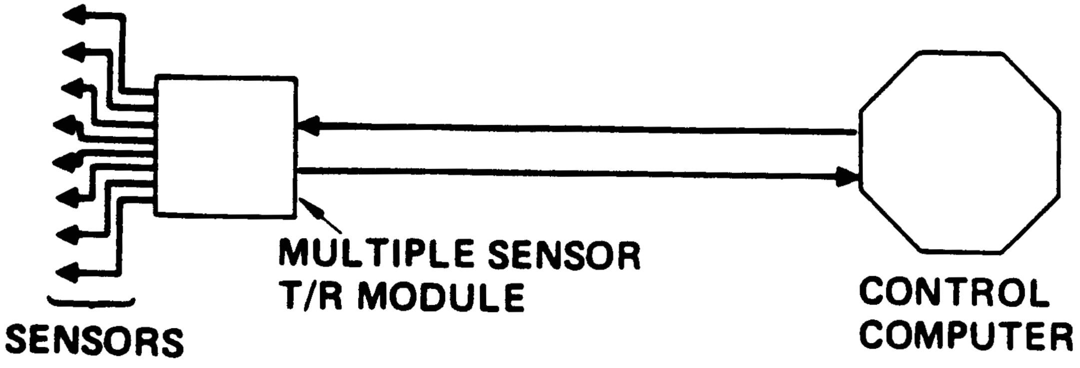

FIGURE 16: MULTIPLE SENSOR CAPABILITY.

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16. Abstract

Geo-orbital systems of the near future will require more sophisticated electronic and electromechanical monitoring and control systems than current satellite systems with an emphasis in the design on the electronic density and autonomy of the subsystem components. This paper describes some results of a project to develop, design, and implement a proof-of-concept sensor system for space applications, with hybrids forming the active subsystem components. The design of the solar powered hybrid sensor modules is discussed and module construction and function is described. These modules combined low power CMOS electronics, GaAs solar cells, a crystal oscillator, standard UART data formatting, and a bidirectional optical data link into a single 1.25" x 1.25" x 0.25" hybrid package which has no need for electrical input or output. Several modules have been built and tested. Applications of such a system for future space missions are also discussed.

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