ICE DRILLING INSTRUMENTATION

by

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ABSTRACT

Two types of instrument packages for monitoring the ice drilling process have been designed. Both are mounted in the drill and return information to the surface while drilling. One was used on a hot water during the November-December 1987 summer season in Antarctica. It was powered and controlled from the surface with the data conversion being done using a commercial board in a Compaq computer. The other design was tested in Greenland during June, 1988. It is battery powered and the data conversion is done by a custom microprocessor and electronics package mounted in an ice coring drill. The data is then returned to the surface serially over two data lines. The designs and types of data collected are discussed as well as possible future extensions of the design to include controlling some of the drilling process.

INTRODUCTION

As the depth of the holes that we are drilling in ice increases, it becomes more difficult to sense the condition and progress of the drill by its current draw or the feel of the cable. Compact, low power, rugged components are available that can be used to build sensor and control packages to fit inside the drill. These will allow a better understanding of the way the drill works so that improvements can be made. They will also allow more control so that drill operation can be made simpler and can be optimized for faster drilling.

HOT WATER DRILL

Previously, hot water drills have usually not been instrumented. A separate logging tool was lowered down the hole to measure the results of the drilling process. In 1987, a hot water drill was being designed to drill a 500 meter deep hole in the Crary Ice Rise (1,2) on the Ross Ice Shelf and it was decided to install sensors inside the drill to monitor various parameters of the drilling process. We designed an instrument package to monitor and record the following variables : depth, inclination in two axes, hole diameter, pressure, and water temperature at four points in the system.

The depth is obtained by having a shaft encoder connected to a wheel which rolls on the hose as it is lowered into the hole. The shaft encoder is connected to a Durant totalizing counter for immediate readout and also to an electronic counting and scaling circuit which triggers a Compaq Portable II to digitize and store data from all the other sensors. The other sensors, which are in the drill, are connected to the surface, electronics interface and power supplies through wires are built into the hose. The hose was custom designed (3) and built for this project and has 34 wires built into it.

The inclination was monitored with two Schaevitz (4) model LSFPA inclinometers with a range of plus or minus 15 degrees. The hole diameter was measured by a Schaevitz Type 3000 HCD Linear Variable Differential Transformer (LVDT) type displacement sensor coupled to calipers mounted on the outside of the drill. The calipers are made of stainless steel strips which are bent into an arch shape. One end of the arch is fastened rigidly to the body of the drill, the other end is fastened to a ring which is free to slide along the surface of the drill. This sliding ring is coupled through a push rod to the sensing element of the LVDT. There are three of these arched metal strips spaced at 120 degree intervals around the drill, and the highest part of the arch is in contact with the wall of the hole. Thus as the hole diameter decreases it compresses the calipers, this radial motion is mechanically converted into a very nearly linear motion of the sliding ring, which moves the sensing element in the LVDT. This system allows measurement of hole diameters from 15CM to approximately 45CM, and has the additional function of holding the drill in the center of the hole.

The inclinometers and LVDT are located in a stainless steel container which fits in a slot inside the drill. Power for these sensors is locally regulated to the required plus and minus 15VDC by Zener diodes, with the current limiting provided by the resistance of the wires carrying the power from the surface. The top of this container is left open to accommodate the push rod for the LVDT. The container is filled with Fluorinert which is a high density, electrically inert liquid made by 3M CORP. This heavy fluid stops water from entering the container and provides insulation for the electrical components. A pressure transducer (Omega Model PX440) (5) is included in the container to monitor the height of the column of water in the hole above the drill. This provides a check on the level of water in the recirculating reservoir and also indicates if water is being lost to hidden crevasses. This open container leaves the sensors exposed to the full pressure of the water column. This caused almost immediate failure of the pressure transducer and one of the inclinometers during the antarctic drilling. The other inclinometer and the LVDT worked without problems to the full 500 meter depth.

Four (Omega type 44032) thermistors are located at various places to monitor the change in water temperature as it circulates through the system. The inlet water temperature is measured at the rotating joint where the heated water is first fed into the hose of the winch. The output water temperature is measured inside the drill before it is expelled and after it has traveled through the 600 meters of hose. The discharge water temperature is measured on the outside of the nozzle of the drill water after it has contacted the ice and is starting to mix with the water in the hole. The caliper temperature sensor is located about 3 meters above the nozzle on one of the calipers. The flow rate of the water in the 2.5CM insulated hose was about 75 liters per minute.

Eighteen wires are used, thus, with the exception of the three sensors sharing the +15/-15VDC power supply, all sensors are current loop types and individually powered from the surface. All sensors, without exception, have separate signal lines returning to the surface. All power and signals pass through an 18 conductor slip ring mounted on the axis of the winch, and then to a display panel box. Underneath the display panel are the power supplies and circuitry for buffering, amplifying, and scaling the signals before they are sent to the display meters and computer. All signals are scaled to conform to the +5/-5 volt input range of the A/D board in the computer. Taut-Band analog meters with custom printed scales from Pacific Indicator are used on the display panel.

A Compaq Portable II computer with a Metrabyte Dash-16 data acquisition board installed is used to collect and store the data. A software package, written at Massachusetts Institute of Technology, called Unkelscope is used to control the data acquisition board, display the raw data in graphical form in real time, and store the data for future use. At a later time, the raw data is exported into the Lotus spreadsheet program for conversion from voltage readings into engineering units. Thus a permanent record of the drilling process can be created for future reference.

CIRCUIT DESCRIPTION

The shaft encoder has a 0.3 meter circumference wheel that rides on the hose and puts out 30 pulses per revolution. There are two outputs that are in quadrature so that directional information can be obtained. Comparators are used to convert these 15 volt pulses into TTL compatible 5 volt pulses (Figure 1). A 7474 integrated circuit is used to determine the direction of rotation and direct the count to either the antibacklash circuit or to the scaling circuit. The scaling circuit divides the count by 25 using two 7490 integrated circuits and then a 74123 shapes the pulse to the requirements of the Metrabyte board in the computer. This causes the computer to do an A/D conversion on the other 8 signals every 1/4 meter. The antibacklash circuit consisting of 3-74193's, 3-7485's, a 7408 and a 7404, allows the drill direction to be reversed for a short distance and then advanced again with the data logging resuming where it had left off before the reversal occurred. A switch on the output of the 7474 allows manual selection of the direction of travel during which the data will be logged and allows the operation of the antibacklash circuit in either direction.

Precision reference voltages are required at various places in the circuitry. They are all derived from a Motorola MC1403A 2.5 volt low drift reference I.C. (Figure 2). Power being provided to the sensors in the drill cause voltage drops in the 600 meter long wires which connect them to the circuitry on the surface. This potential signal error source is overcome by using a separate ground sense line and buffering it and the signal lines with high impedance low drift amplifiers. This method is used on the LVDT and Inclinometers which produce voltage outputs (Figure 3). The analog display meters used for these signals use a +/- 5 volt center zero meter movement with custom scales.

The pressure sensor (Omega PX440) has a 4-20ma current loop output, thus the resistance of the wires is unimportant except in the determination of the power supply voltage (Figure 4). In this case, the 110 ohm resistance of the wire dictated a 35 volt supply for this sensor. A 500 ohm resistor is used as a current to voltage converter and this signal is buffered by a low drift amplifier before it is applied to a 10 volt left zero meter with a custom scale printed to show zero PSI with a 2 volt input and 1000 PSI with a 10 volt input. The 2 to 10 volt signal is amplified and offset to provide a +/- 5 volt signal to the computer.

The 4 temperature sensors are thermistors which vary their resistance as a function of

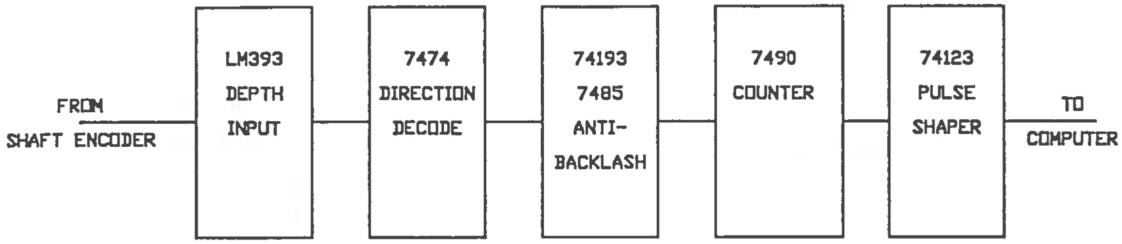

FIGURE 1. BLOCK DIAGRAM OF DEPTH RECORDING CIRCUIT.

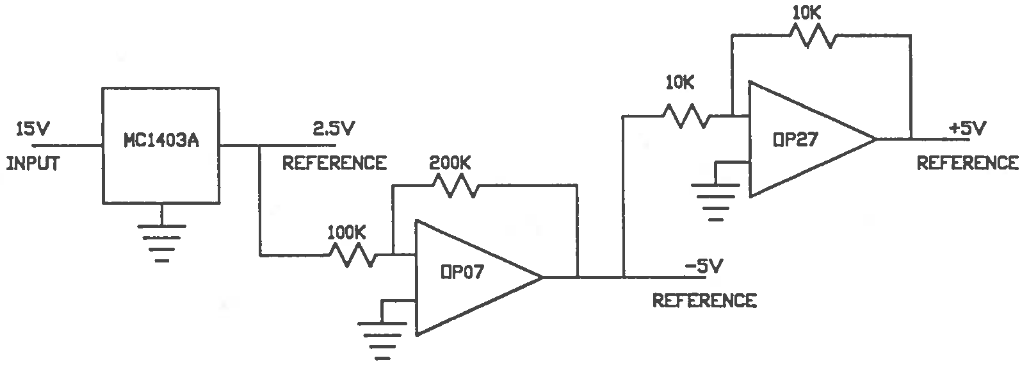

FIGURE 2. DIAGRAM OF VOLTAGE REFERENCE CIRCUIT.

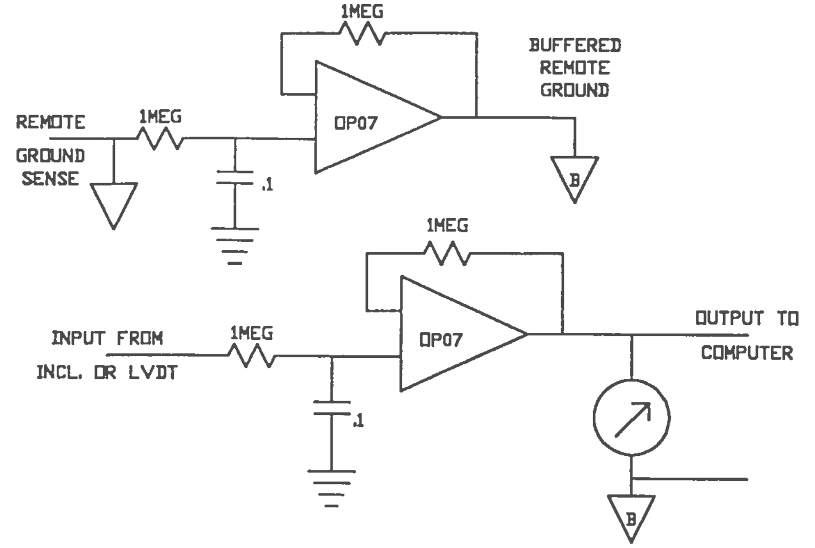

FIGURE 3. CIRCUIT DIAGRAM FOR SENSING REMOTE SIGNALS.

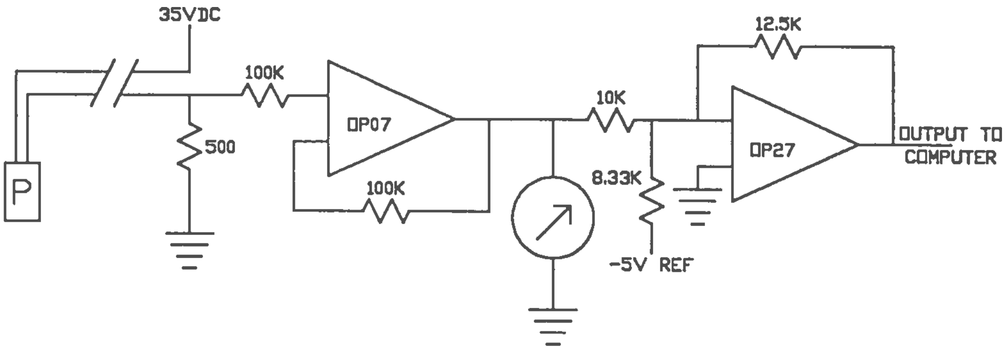

FIGURE 4. PRESSURE SENSING CIRCUIT.

temperature, thus the resistance of the connecting wires must be included in the calculations. A fixed voltage is applied to the thermistor (Figure 5) and the current that flows through it is converted to a voltage, and simultaneously offset to provide the +/- 5 volt signal needed by the A/D board in the computer. A high value thermistor (30k @ 25 degrees centigrade) was chosen to minimize the effect of the wire resistance. The output of this circuit is nonlinear and inverted, thus the 10 volt left zero meter has a custom nonlinear scale printed to show -40 degrees with a 0 volt input and +100 degrees centigrade with a 10 volt input. The temperature is calculated in the computer by using an equation which recovers the resistance of the thermistor from the input voltage and then using a lookup table derived from the calibration curve for the thermistor.

ICE CORING DRILL

An ice coring drill has been designed at PICO to be used in Greenland to drill a deep fluid-filled hole (6). In contrast to the large number of wires available in the hose for the hot water drill just described, only 7 wires are available in the cable for the ice coring drill. This limited number is due to manufacturing considerations and also due to the great length of the cable. More wires in the 1165 meter Kevlar reinforced cable would add a great deal of weight and bulk to the cable and to the winch used to carry it. To transmit a large amount of power to the drill over the small wires available in the cable, we transform the 240VAC input to 480VAC at the surface. Four of the available wires are used to carry the high voltage AC power to the drill where it is transformed down to 120VAC and converted to DC current for the drill motor. This leaves only three wires to carry control signals between the drill and the surface. An instrument package has been designed to go into the ice coring drill to monitor various parameters in the drill and to transmit that information back to the surface for display and storage. The instrument package in the drill also receives commands from the surface to control the direction of the drill motor as well as some other aspects of the package operation. Due to the large number of parameters to be monitored and the high speed communications needed for control the instrument package is designed around a high speed microcontroller with a built in serial I/O port. The electronics circuitry that goes in the drill is contained in an aluminum pressure vessel that is sealed with O.Rings and has high pressure electrical feedthroughs. This pressure vessel is the same diameter as the rest of the drill and forms a structural member of the drill assembly. The electronics circuitry that remains on the surface is mounted on a control panel that fits inside the box containing the power control for the drill motor.

The parameters that are monitored are : depth, inclination in two axes, azimuth, motor RPM, motor voltage, motor current, fluid pressure and temperature in the hole, air pressure and temperature inside the pressure vessel, battery voltage and cable tension. The depth is measured at the surface using a shaft encoder mounted on the axle of the sheave at the top of the drill tower. The pulses from the shaft encoder are in directional quadrature and are counted by a Durant counter/display and also by a microprocessor in the control panel. All the other signals are measured by the electronic circuitry in the drill.

The microprocessor in the drill controls a 16 channel 12 bit data acquisition subsystem (Model AD364SD) manufactured by Analog Devices (7). It also controls four relays which have the following functions : battery charging relay, drill reversing relay, drill stop relay and sensor power relay. The microprocessor is an 87C51 manufactured by Intel (8). It is programmed to wait for a control command from the control panel at the surface which tells it which relays to turn on/off, when to enable the data acquisition subsystem (DAS) and when to transmit the data to the surface.

The control panel also contains an 87C51 microprocessor. This microprocessor is programmed to monitor the switches located on the control panel and send control commands to the drill in response to switch changes. It also counts pulses from the shaft encoder to monitor drill depth. It receives the raw data from the drill and stores it temporarily for display on the control panel. The bulk of the program in the control microprocessor does an immediate conversion of the raw data into actual numbers for display on the control panel. When the sensor power switch on the control panel is on, new data is acquired, converted and displayed three times each second. When data logging is enabled by a switch on the control panel, data to be permanently stored is sent to Compaq Portable II computer every 20 cm of change in drill depth. Communication with the Compaq computer is via it's standard serial interface port and the data is stored in a Lotus spreadsheet by a communications program called Lotus Measure.

CIRCUIT DESCRIPTION

The electronics circuitry in the drill is designed around an Intel 87C51 microcontroller (Figure 6). This is a complete microcomputer on a chip. It has built in EPROM program memory, RAM data memory, CPU, I/O ports, and serial communication port. The 87C51 in the drill communicates with the control panel at the surface, executing commands sent to it and returning data to the surface. These commands determine the status of the four relays and of the data acquisition process (Figure 7). The stop relay is used to disconnect AC power from the AC to DC converter and thus remove power from the drill motor. This allows the reversing relay to reverse the polarity of the DC current to the motor without excessive arcing. The battery charge relay is used to connect the battery to the DC motor voltage through a resistor so the battery can be partially recharged while the drill is running. A 12 volt gell cell type lead acid battery is used to provide power for the electronics package in the drill due to the limited number of conductors available in the drill cable. The components in the electronics package were chosen both for cold temperature operating ranges and for low power operation to minimize battery drain. The sensor power relay (Figure 6) allows the package to be put in a very low power standby mode by disconnecting the data acquisition system and sensors from the battery. In this standby mode, the 87C51 and DS3696 driver chip together only draw about 50MA, but are still fully active and can still control the relays. An even lower mode is possible, but has not been implemented, whereby the 87C51 itself can be put in a standby mode. When the DAS is enabled, it and the sensors draw about 500 MA from the 12V battery. The battery has a 12 amp hour rating and thus could carry this load for a number of hours depending on temperature. Most of the 500MA is used by the (Calex Model 12D15.100) 12V to +/- 15V converter which supplies the voltages required by the sensors ans DAS.

The AD364 DAS consists of two chips, an AD574 12 bit 35 microsecond analog to digital converter and an AD362 sample and hold and 16 channel multiplexer. The 87C51 controls both of these chips using one its I/O ports and receives data from the A/D

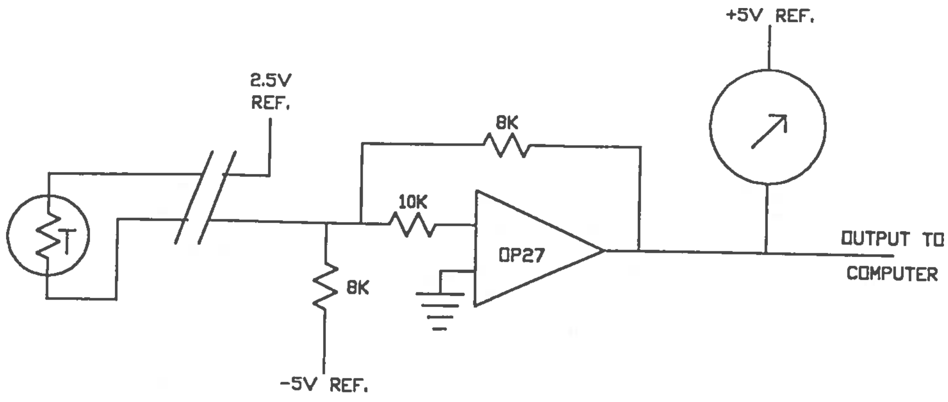

FIGURE 5. TEMPERATURE SENSING CIRCUIT

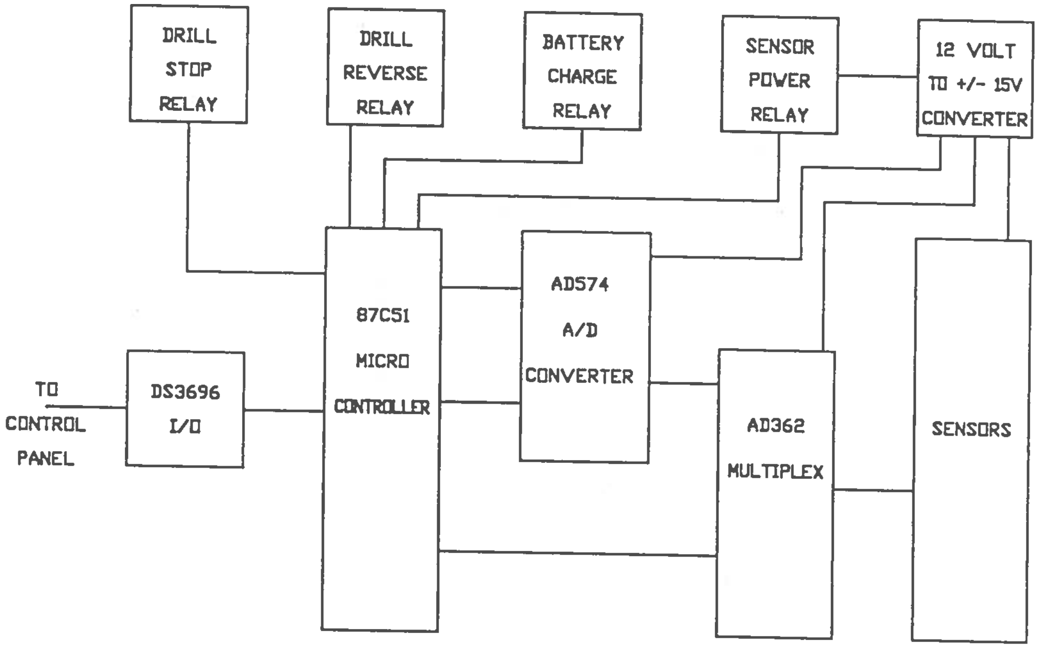

FIGURE 6. BLOCK DIAGRAM OF CIRCUIT IN ICE CORING DRILL

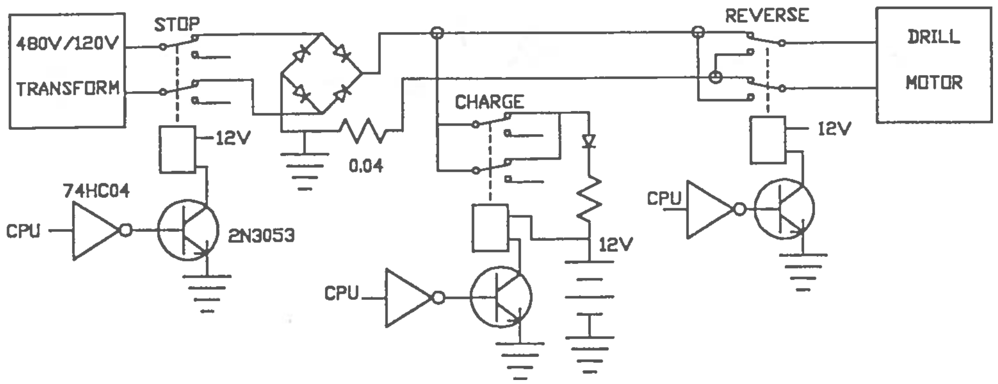

FIGURE 7. DIAGRAM OF HIGH POWER CIRCUIT IN DRILL

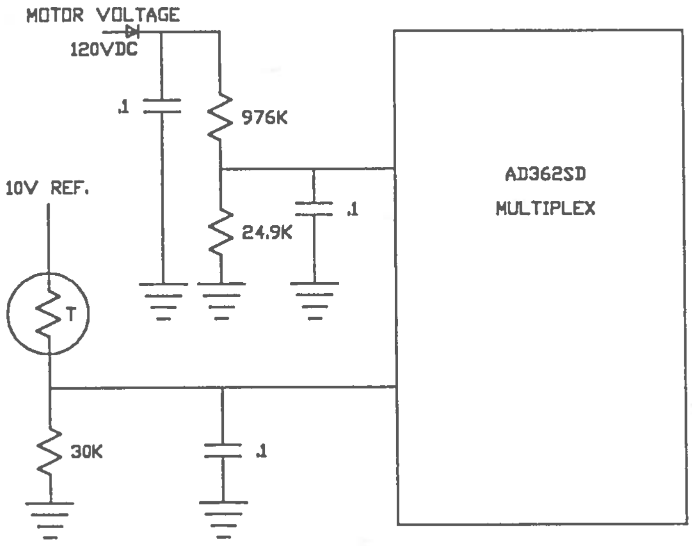

FIGURE 8. EXAMPLE OF SIMPLE CONDITIONING REQUIRED FOR SIGNALS

converter through another of its I/O ports. The 87C51 causes the multiplexer to step through the 16 signals that are available and present them one at a time to the A/D converter. The A/D converter then converts the signal to a digital value which is stored in the 87C51 until all channels have been converted. The data is then transmitted to the control panel at the surface.

The inclination is measured by two Schaevitz (part 2338-03) inclinometers which have an output of 60 MV per degree of tilt. A Watson (9) (Model FGM200A) three axis fluxgate magnetometer is used to provide both a cross check on the inclinometers and an azimuth indication. The output of each magnetometer axis is 1 volt per 250 milligauss. The motor current is measured by placing a .04 ohm resistor in the motor power wiring and measuring the voltage across it. This provides a signal of 1V/25AMPS. The six signals just described require no buffering or scaling. They are usable directly by the +/- 5 volt input range of the A/D converter. Having the DAS close to the signal sources eliminates the problem of voltage drops and noise in long signal lines. Also, by having a digital readout on the control panel, all the scaling and level shifting is done by the microprocessor thus eliminating a lot of analog circuitry such as that used in the hot water drill display panel shown earlier.

Omega pressure transducers (type PX176) are used to monitor the fluid pressure in the bore hole and the air pressure in the sealed cylinder that contains the instrument package. These transducers have an output range of 1V to 6V and thus a simple resistive voltage divider is used to bring the signal within the input range of the A/D converter. The air pressure in the cylinder is monitored to determine if fluid is leaking into the cylinder under the high pressures expected in the bore hole. Other signals that need resistive dividers to bring them within the correct A/D input range are motor rpm, motor voltage, battery voltage and the 10V system reference. The motor rpm signal produced by a tachometer in the motor is 10V/1000RPM and can be as high as 50 volts. Motor voltage can be as high as 120VDC. Temperature measurement is much simpler with a microprocessor because the nonlinear resistance verses temperature curve of the thermistor can be corrected in software. Thus, the simple resistor circuit shown in Figure 8 along with a calibration curve in memory is all that is required to obtain a temperature signal. The thermistor used is an Omega type 44032.

The tension in the cable (minus the weight of the cable) is measured by a load cell which is mounted so that it provides the connecting link between the cable and the drill. The information provided by this sensor indicates the weight on the cutters while drilling, the tension required to break the core, the drag of the antitorque skates on the hole wall as the drill is being retrieved and the weight of the core and chips being returned to the surface. The load cell used (Omega Model LCC) has no internal signal conditioning circuitry, so the circuit in Figure 9 provides this function. The 10V at 22MA required to power the load cell resistor network is beyond the capability of the precision opamp used to produce the system 10V reference. By adding the 223 ohm resistor from the + 15V supply, the 22MA current requirement is met, thus the system reference only has to provide very small correction currents to maintain the precision 10V input required by the load cell. The output of the load cell is only 30 millivolts for a 5000LB load, thus a great deal of amplification is required to provide a usable signal. The Analog Devices AD625B instrumentation amplifier circuit provides a gain of 417 which gives a signal of 1V/400LB.

The electronics circuitry in the control panel is also designed around the 87C51 microcontroller (Figure 10). The signals from the shaft encoder are filtered and level shifted by the LM393 comparators and then go directly into an interrupt input on the 87C51. An interrupt service routine then determines the direction the cable is moving and updates the depth count in memory. A Durant counter provides a backup count and display, but, since the sheave is not the same circumference as the wheel the shaft encoder was designed for, the readout provides a number proportional to depth rather than the actual depth. The 87C51 can be reprogrammed for any wheel diameter so that the readout it provides is the actual depth in meters. The two CD4532's and a CD4071 encode 16 switches into 4 input port pins of the 87C51. Another 6 switches are attached to 6 other input port pins. The microprocessor interprets the switch setting and based on these settings either sends commands to the drill, displays requested data on the front panel, or sends data to the external computer to be logged. When the readout select switch is turned to the desired signal, the 87C51 retrieves the raw data most recently received from the drill, does a calculation to put the data into readable form, outputs the result to the CD4511 latches which drive the LED displays. It then updates the display it new information is received from the drill or the display select switch is changed. Communication with the drill uses the same bidirectional differential transmission line driver (National Semiconductor DS3696) (10) as is used in the drill. This chip is connected to the 87C51's serial I/O port through a relay controlled by the 87C51. When data is to be logged to the external computer, the relay connects a serial line driver (Maxim MAX232) (11) to the microcontroller's serial I/O port. The control panel circuitry all operates on 5V only, so the MAX232 chip has internal converters and inverters to provide the +/- 12V signal levels required to communicate with the serial port on the external computer.

A program called Lotus Measure controls the serial port on the Compaq II portable computer to accept the data from the control panel and store it in a Lotus 123 spreadsheet. The data sent to the computer is the same raw data that the control panel had received from the drill. This allows higher precision calculations to be performed on the data than were possible in the microcontroller due to program size limitations.

CONCLUSION

The two instrument packages described in this paper are first generation designs for PICO and were designed, constructed and used within the past year. The microprocessors in the ice coring drill were capable of doing a great deal more than they were asked to do in this design. We plan to do more work on closing the control loop for a number of drilling processes. For example, the microprocessor could monitor the azimuth for spin caused by slippage of the antitorque system, then stop the drill and either notify personnel on the surface or automatically correct the problem itself. The repetitive tasks of raising the drill to the surface to retrieve the core and then lowering it again could be automatically controlled. The drill motor speed could be controlled in the drill with only a digital command from the surface to specify a speed to maintain. High speed data acquisition and communication allows much better visual indicators to be available to the

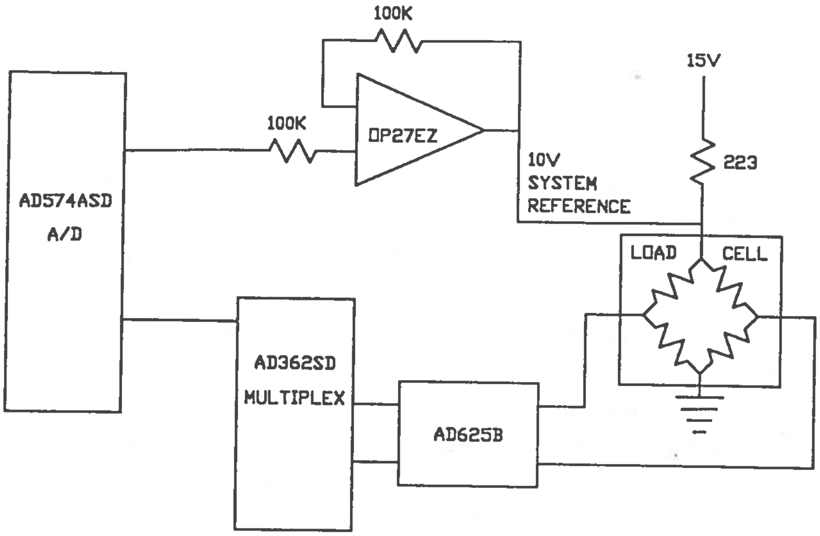

FIGURE 9. DIAGRAM OF LOADCELL CIRCUIT

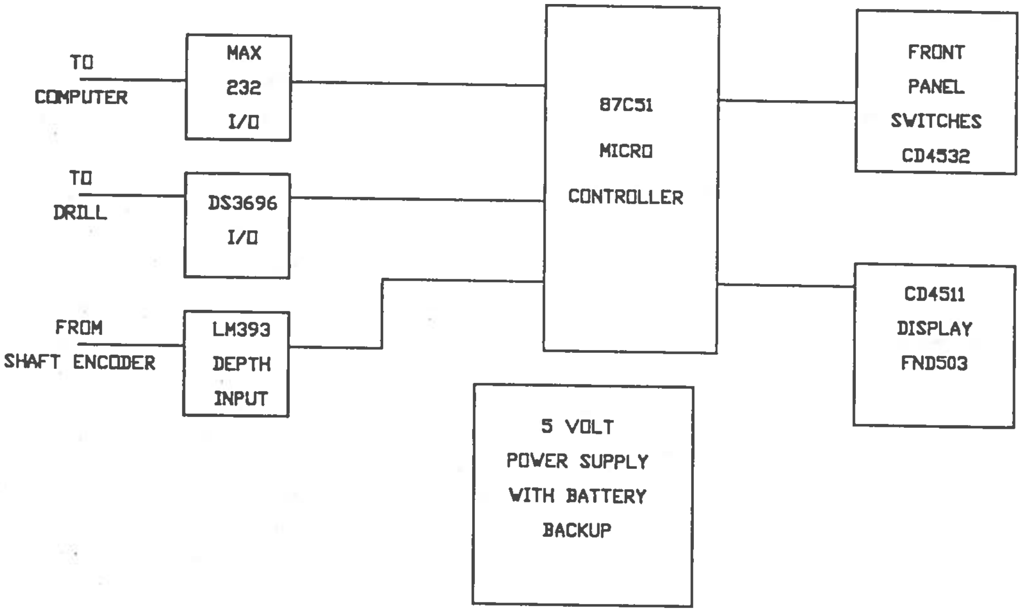

FIGURE 10. BLOCK DIAGRAM OF CONTROL PANEL CIRCUIT

personnel on the surface. The extremely long cables now coming into use seem to act like springs when a heavy drill is on the end of them. This makes it almost impossible to precisely control drill bit pressure and drilling rate by pulling or pushing on the other end of the spring. A jack screw mechanism could be installed in the drill itself along with force and displacement sensors which would allow a microprocessor in the drill to precisely control the drilling process locally. This could provide for a smoother penetration rate for higher core quality.

We are exploring the possibility of using a fibreoptic cable as a higher speed communication link in the drill cable. This would eliminate electrical interference problems between the power conductors in the cable and the communication conductors in the same cable.

In conclusion, it seems that we are just beginning to scratch the surface in applying new electronics technologies to improve the art of ice core drilling.

ACKNOWLEDGEMENTS

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