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A FLEXIBLE CONTROL, COMMUNICATION, AND DATA COLLECTION NETWORK FOR MINING MACHINES

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Abstract--The U.S. Bureau of Mines has integrated off-the-shelf components into a microcomputer-based control, communication, and data collection network that provides a base for computer-controlled mining machine research and coal production applications. Functions provided by the network include closed-loop control, teleoperation, navigation, data collection, and diagnostics. These functions are all provided to help pursue the Bureau's goal of moving the man off of the machine and to a safer area. The installation of the network or a Joy 14CM continuous mining machine has accelerated the collection of data and the generation of navigation and control algorithm. The demonstrated functions of the system lends itself to potential use on other mining machine types.

INTRODUCTION

As new computer hardware and software technology becomes available, it is always tempting to apply it to existing engineering problems, with the hope of finding better solutions to those problems. In a system with several interacting subsystems, this methodology often creates a new problem: do you throw out all the old hardware and software, or do you try to make the old compatible with the new? As applied to the computerization of coal mining machines, the Bureau has attempted to resolve this dilemma while pursuing the machine automation goal, by designing a system composed of discrete subsystems dedicated to specific tasks. Each subsystem is as autonomous as possible, but has the absolute requirement that each subsystem can interact with other, sometimes older, subsystems in a deterministic (guaranteed delivery of data in a specific length of time) manner. Logically, it follows that a network of computers would be required to meet these design requirements. This paper details the chosen network and describes its implementation.

NETWORK SELECTION

The Bureau's system design requirements were to have discrete subsystems dedicated to specific tasks, with each task being as autonomous as possible, and to provide each task with the capability of interacting with each other in a deterministic manner. Based on the Bureau's previous experience with a collection of hardware and software identified as BITBUS[1] [1], the Bureau selected BITBUS as a good match of network capabilities to performance required. BITBUS is a nonproprietary open architecture serial communication standard developed by the INTEL Corporation especially for industrial control applications. The Bureau named this unique implementation of BITBUS "BOM/NET."

BITBUS DEFINED

BITBUS is defined at four levels: electrical interface, data link protocol, message protocol, and application. The electrical interface is based on the RS-485 standard. It provides multi-drop support over a twisted pair line with communication rates up to 2 mega bits per second (mbps). The twisted pair line is differentially driven making the line noise resistant. This is especially important for the BOM/NET implementation of BITBUS because of the unusually harsh electrical environment in a coal mine. The electrical interface supports up to 28 nodes on a cable segment, with up to 250 nodes in a fully loaded network using repeaters between cable segments. The Bureau's implementation of BITBUS was specified for a single 1,000-ft cable segment with a maximum of 16 nodes, and a communication speed of 375 kilo bits per second (kbps).

The data link protocol is based on a subset of the International Business Machines (IBM) Synchronous Data Link Control (SDLC) standard. SDLC is a proven reliable protocol for interconnecting a master node to multiple slave nodes in a multi-drop topology. The standard data link frame format supports node addressing, data link control functions, message transfer, and error detection. Messages are transferred in the information field (Fig. 1) of the frame. The data link protocol supports message transfer with this frame format in two ways: bit error detection in the frame check sequence (FCS) field and sequencing of transfers in the control field. The FCS field contains a 16-bit cyclic redundancy check (CRC) used to detect bit errors on the link. The master node exchanges messages with a slave node using standard SDLC supervisory and information control fields. BITBUS uses information control fields to transfer messages, but uses supervisory control fields to perform data link

[1]Reference to specific products does not imply endorsement by the U.S. Bureau of Mine.

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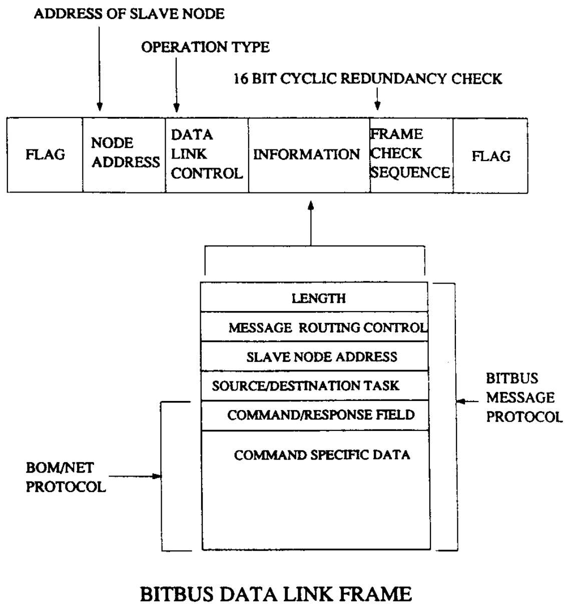

Fig. 1. BITBUS protocol.

control functions when messages are not available. These include a slave node acknowledging receipt of a frame from the master node or the master node polling a slave node for a message. These capabilities allow messages sent to slave nodes to be immediately acknowledged by the hardware interface. Automatic acknowledgment frees up the link for the master node to perform other operations such as sending a message or polling another slave node. This maximizes the serial bus utilization and thus system performance.

BITBUS defines the message protocol within the data link protocol (Fig. 1) and is always 20 bytes long for BOM/NET. The message protocol defines the message structure for the information field. It also defines the order-reply mechanism for communication between tasks on the master node and tasks on the slave nodes (a task is generally considered to be an instance of a program in execution). The message format provides an addressing mechanism to route messages to a specific task on a specific node. The message protocol uses an order-reply mechanism to pass messages between tasks at the master node and at slave nodes, as well as between tasks on a master or slave node. This protocol specifies that tasks on the master node issue orders to tasks on the slave nodes that, in turn, respond with replies. The data link protocol supports the exchange by transferring the order message in an information frame. The receiving slave node immediately acknowledges the order message with either a supervisory frame or an information frame if the reply from a previous order is available. The master node then polls the slave node until it returns the corresponding reply message. This polling may be performed with either a supervisory frame or, if additional order messages are available, with information frames. This algorithm minimizes unnecessary polling since a slave is only polled when one or more (maximum of seven) orders are outstanding to it. The algorithm maximizes performance by allowing polls and acknowledges to be piggybacked on order and reply messages, respectively.

Subsystem tasks interface directly to the message protocol. There are at least two subsystem tasks defined in every network node. One is called the Remote Access and Control (RAC) task, and the other is called the Communications Handler Task (CHT). The RAC task permits network access to the I/O in a node. The CHT task is dedicated to communications management that includes a message protocol encoding and decoding scheme that uniquely specifies command and data packets for each node.

BOM/NET MICROPROCESSOR DESCRIPTION

Each node in BOM/NET has a microprocessor board that performs a system function or works with an attached external device to provide a system function. Each node is based on a central processing unit (CPU) called the INTEL 8044 microcontroller. The 8044 is a member of the INTEL 8051 microcontroller family. The 8044 provides a 8051 CPU core and a serial interface unit (SIU). The SIU is an independent processor that provides the SDLC protocol directly in hardware. This approach relieves the 8051 of all routine communications overhead, allowing it to be dedicated to control functions. The two processors communicate through a time multiplexed two-port random accessed memory (RAM) area. This permits both processors to run concurrently at their full speed of 12 MHz (instruction cycle is 1 μs). The 8044 also includes a small (2 kbytes) real-time multi-tasking operating system in read only memory (ROM) called iDCX51 [1]. The iDCX51 provides the BITBUS message passing protocol for multi-node and on-node, message passing, and it also contains the RAC task. The RAC task, iDCX51, and the application tasks, on each node begin executing as soon as each node is powered up.

Many vendors can supply the hardware and software for producing a system like the Bureau's. A partial list of such vendors is provided at the end of this paper [2].

BOM/NET ON A COAL MINING MACHINE

The Bureau has installed BOM/NET on several mining systems, including a Jeffrey 102CM, a Joy 16CM and Joy 14CM. The Joy 14CM, will be described here. Fig. 2 shows the Joy 14CM system when it was in the Bureau's surface test facility in Bruceton, PA. This system is now undergoing testing in an underground coal mine in West Virginia. The Joy 14CM has several controllable parts, including a conveyor (transports the coal from the front of the machine to the back), a shearer (cuts the coal), a gathering head (collects the freshly cut coal), a stabilizer jack (levels the machine), and a pair of tracks for mobility. Both electrical and hydraulic systems power the machine.

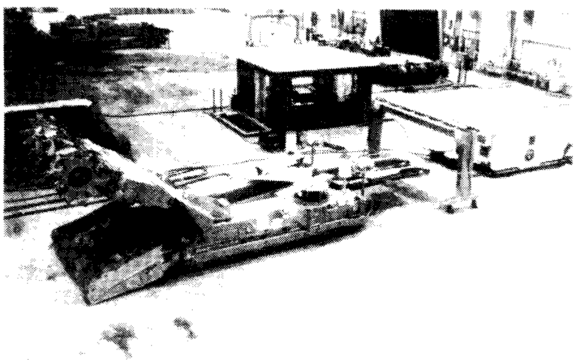

Fig. 2. Picture of the Joy 14CM in the surface test facility.

One objective of the Bureau's research is to move the human operator off the machine to a safer area. For this purpose, the Bureau designed and constructed a control hut for the operator, which can be up to 500 ft from the machine. The Bureau added BOM/NET, assorted sensors, and external computers systems to the control hut and the machine. BOM/NET as applied to the Joy 14CM is shown in Fig. 3. The bubbles in the figure are nodes in the network, and they represent one BITBUS card (a card is a node). The blocks (the blocks and circles are sometimes collectively referred to as a node) in the figure represent externally connected computer systems which are connected to BOM/NET through a BOM/NET gateway. The CM node (node 1) provides closed-loop and open-loop control of all the Joy 14CM moving parts. Additionally, it provides access to all sensor data. The Gyro (node 2) is a face navigation system [3] that uses an inertial gyroscope. The Laser node is a face navigation system [4] that uses two lasers and two machine-mounted reflectors to give the position and heading of the Joy 14CM. The laser node is composed of a computer system that is connected to BOM/NET through a BOM/NET gateway (node 3). The Mechanical Position and Heading System node (mphs) [5] (node 4) is another face navigation system that uses linear displacement transducers. The Remote Operator and Diagnostic Node (RODNE) (node 5) is a handheld network diagnostics tool. Gateway node 7 connects AMREDS [6], a software program that operates on a SUN workstation [7], to BOM/NET. This software application serves as a system viewport, a manual command center, an environment for script development, a platform for control program development, a graphical display device for the Joy 14CM appendage positions during operation, and other functions. The Camera Control/Machine Status node (node 8), on board the machine provides remote control of Joy 14CM-mounted video cameras. It also provides monitoring of a collection of machine-mounted sensors. The Remote Control node (node 9), in the control hut, provides remote control of the Joy 14CM-and cameras (through node 8) that are mounted on it. The Mining Machine Graphical Display node [8] is a BOM/NET gateway (node A) tied to a NEC-AT [9] computer that collects machine status data from the CM node and presents it graphically to the system operator. The Electrical Diagnostics (ED) Node (node B) collects data from various Joy 14CM mounted sensors, and presents its analysis locally on a two-digit LED and also provides its analysis over the network. The Master node (node F) acts as communications manager of the network, routing the data from node to node.

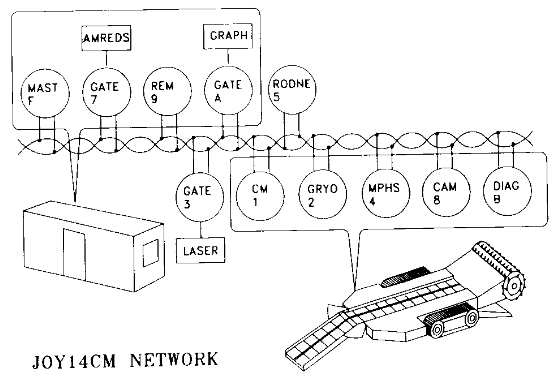

Fig. 3. Picture of the Joy 14CM in the surface test facility.

BOM/NET COMMUNICATIONS PROTOCOL FOR THE Joy 14CM

All communications between nodes strictly conform to the BITBUS standard. Embedded within the BITBUS message protocol packet (Fig. 1) is a unique implementation of the BITBUS protocol that the Bureau calls BOM/NET Protocol. This protocol works in conjunction with one software task (the CMT) in each node to provide a method of communicating from node to node without concern for the master/slave relationship of nodes in BITBUS. The protocol is essentially a simple set of rules that identifies how data are retrieved from a node or how a function provided by a node is activated. Also the protocol specifies how each node should respond to commands or requests for data. These rules are collectively identified as packets. For BOM/NET there are six different types:

Command Packets	(CP)
Command Acknowledge Packet	(CAP)
Command Failure Packet	(CFP)
Command Execution Completion Packet	(CECP)
Command Execution Failure Packet	(CEFP)
Command Execution Preemption Packet	(CEPP)

Descriptions:

CP - provides control functions and also provides access to the status or data associated with some device.

CAP - is sent in response to a CP that acknowledges that the command is recognized as a valid command but does not mean the command was executed successfully.

CFP - is sent in response to a CP if the received packet is not a command recognized by a node, or contains unknown or corrupted data.

CECP - is sent after a CP has been successfully executed in compliance with the CP target parameter value or data request.

CEFP - is sent if a CP was not successfully executed.

CEPP - is sent when a previously activated process has been interrupted and a new process is begun, based on data contained in the new packet.

Each node of BOM/NET defines various combinations of these packets to provide a specific system function. Gateway nodes are the exception. The external computer must define them. There are many packets defined for the whole BOM/NET system. The following AMREDS-to-Joy-14CM interaction gives the reader a flavor for the types of data that are produced:

> AMREDS commands the Joy 14CM to move its conveyor up 5°. The CP sent by AMREDS to node 1 is #140005cr. Node 1 immediately responds to AMREDS with #10040cr, which is a CAP. There are a few second time lag until the Joy 14CM completes this command (because of slow hydraulics). Joy 14CM mounted sensors that connect to node 1 verify the final position of the conveyor. When node 1 detects that the conveyor has reached it target, it responds to AMREDS with a #1FC40000cr, which is a CECP. This is a final acknowledgment from node 1 that the conveyor reached the final target position.

Similar packet interactions occur between all nodes of the network.

SPEED AND DETERMINISM

Each node active in the network adds a 2 to 3 msec delay to the network throughput, giving the network a predictable determinism. Mainly because of the round-robin scheduling algorithm the master employs. It follows that if all 16 nodes are active, the delay would be a 32 to 48 msec. The master, however, has a bank of switches that permits the human operator to select only the nodes that he needs at the time. If the operator only needs nodes 1 and 6 for an application, he can reduce the network throughput, delay to 4 to 6 msec, giving him the best possible network performance. This kind of network customization is most useful for applications like teleoperation and data collection, which require a high throughput.

TELEOPERATION

Nodes 1, 8, 9, and A provide teleoperation of the Joy 14CM. This mode of operation is heavily dependent on the human operator's ability to see and his intuition. In this mode the operator manipulates a bank of switches (Fig. 4) that corresponds to control functions for the Joy 14CM machine. His actions are echoed at the Joy 14CM. He verifies the results by watching the output of two machine-mounted cameras on two TV monitors housed in his control hut. He also can watch graphical displays of critical Joy 14CM parameters. Teleoperation, as described here, can also be called open-loop control.

CLOSED-LOOP/OPEN-LOOP CONTROL

Closed-loop control of the Joy 14CM requires less network overhead than open-loop control. A closed-loop command, such as "move the conveyor to 5°" (sent from node 6 to node 1), executes entirely on node 1, and requires the transmission of only one command packet over the network. By contrast, an open-loop command, such as "move the conveyor up" (sent from node 6 to node 1), requires node 6 to poll node 1 repeatedly until the "conveyor up" sensor indicates that the conveyor is at 5°. Depending upon node 6's polling rate, this interchange could require hundreds of commands to be sent before the conveyor gets to its target value. Naturally, closed-loop control of the Joy 14CM is the most commonly used feature of BOM/NET.

NORMAL OPERATION

AMREDS is usually the primary computer interface used to operate the Joy 14CM. It provides joystick, simulation, and scripting functions. The joystick mode allows the operator to control individual parts of the Joy 14CM. The simulation mode allows the operator to construct long scripts of Joy 14CM functions that a wire-frame model of the

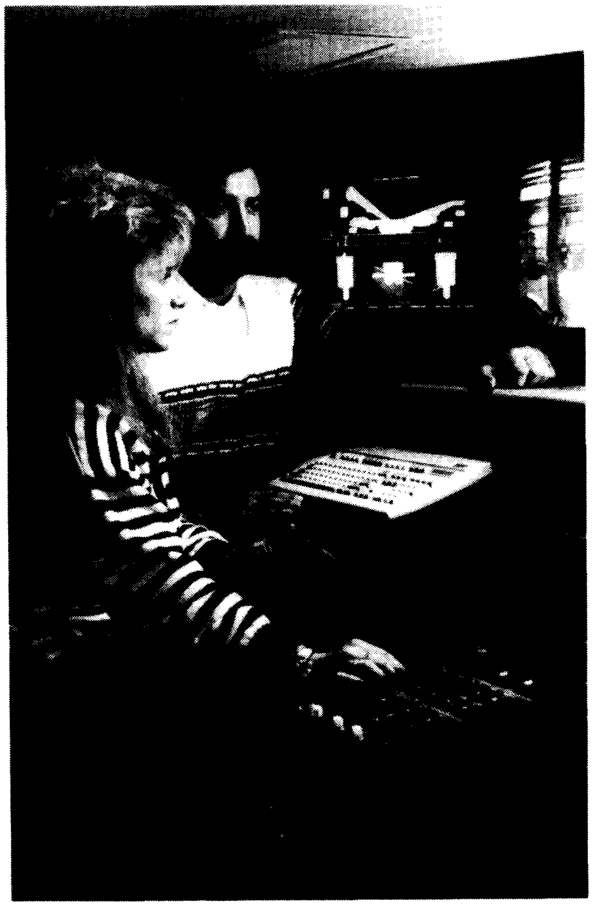

Fig. 4. Inside the control hut.

Joy 14CM performs sequentially on the local monitor. None of the commands in the simulation mode ever go to the Joy 14CM. The scripting mode allows the operator to select from any number of previously created scripts. Scripts can contain complete power-up and coal production cycles as well as Joy 14CM shut down. The scripts can access navigation data to insure that the Joy 14CM stays on its pre-planned path. The script can be dynamically altered if conditions change during the mining process. The operator of the system can watch the outputs of all the sensor systems of the Joy 14CM on the AMREDS monitor to insure all systems are functioning properly. The operator can stop any active process by hitting any key on the AMREDS keyboard. Present plans call for archiving long scripts of field data of Joy 14CM human operator interactions while producing coal. The Bureau will then run the Joy 14CM at its surface test facility using scripts created from these field data. This type of analysis will help to fine tune software algorithms to mimic real production operations closely.

CONCLUSIONS

The U.S. Bureau of Mines has integrated a distributed processing network called BOM/NET and installed it on a Joy 14CM. The network functions as a communications and control system that permits computers and intelligent sensor systems to interact with the machine while the machine produces coal. The installation of the network has accelerated the collection of data and the generation of intelligent navigation and control algorithms. The demonstrated functionality of the system lends itself to potential use on many other mining machines rather than just on the Joy 14CM. With this document, the Bureau hopes to promote the network to others concerned with providing computer-assisted control of mining machines.

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[2] Vendor list: Computer Dynamics, 107 S. Main Street, Greer, SC 29651; Cincinnati Electronic Systems, 420 Wards Corner Road, Loveland, OH 45140; Datem Limited, 148 Colonnade Road, Nepean, Ontario, CANADA K2E 7R4; Micronetics, P.O. Box 347, Greendale, WI 53124; Datel, 11 Cabot Road, Mansfield, MA 02048.

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[6] Ausefski, D. L. Researcher's Interface Software for Computer-Based Mining System Development and Testing. Proc. of the Tenth WVU International Mining Electrotechnology Conference, Morgantown, WV, July 24-27, 1990, pp. 130-133.

[7] SUN 3/160 Workstation, SUN Microsystems, Mountain View, CA.
[8] Graphics Node (No further details available at this time).
[9] NEC Powermate 386/20 AT computer. (No further details available at this time).

CAPTIONS

Figure 1. - BITBUS Protocol.

Figure 2. - Picture of the Joy 14CM in the surface test facility.

Figure 3. - Picture of the BOM/NET system for the Joy 14CM.

Figure 4. - Inside the control hut.