Flexible Control Networks in Mining Machines to Improve Worker Safety

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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 worker off the machine and to a safer area. The installation of the network on a Joy 14CM continuous mining machine has accelerated the collection of data and the generation of navigation and control algorithms. The demonstrated functions of the system lend themselves to potential use on other mining machine types.

Coal Mining — Background

Research is being conducted by the Bureau to make mining safer for the worker by minimizing hazards. Additionally, the Bureau seeks to increase worker efficiency by providing machines with enhanced capabilities employing the latest computer technologies.

The present research is concentrated on the coal mine face area (coal extraction point). A typical face area is shown in Fig. 1. It includes a continuous miner which extracts the coal, a roof-bolter which provides a means of securing the roof where coal has been extracted, and a shuttle car which transports the coal from the face area to a conveyor belt. The conveyor belt transports the coal to the surface where it is usually processed into a cleaner product. In general, the face machinery is powered from a central point using ac power. The workers in such mine face areas are exposed to numerous safety hazards including being crushed by roof falls, being injured by mine equipment, explosions, coal dust inhalation, loss of hearing, and electrocution. The inefficiencies of such a face area are usually caused by equipment failures, slow transport of coal from the continuous miner to the conveyor belt (shuttle car delays), and maintenance of the equipment.

Surprisingly, computer technology is not used widely in coal face production machines, although it is apparent that computers could be of great benefit. The Bureau is addressing this situation and this paper identifies some of its efforts.

Computerization of Coal Mining Machines

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

Based on the Bureau’s previous experience with a collection of hardware and software identified as BITBUS [1], the Bureau selected BITBUS as a good match for 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 complete standard has been given the Institute of Electrical and Electronic Engineers (IEEE) designation IEEE P111.8. An important feature of this standard is that it embraces all levels of the International Standards Organization/Open Systems Interconnect (ISO/OSI) reference model.

Some of the features of BITBUS which were especially attractive were that individual nodes can be added or removed by turning off their power; single node failures will not cause the whole network to fail, unless it is the master node; and the fundamental network communication is completely handled by built-in firmware, leaving only application-dependent software to be developed by the Bureau personnel. Other networks may have similar characteristics and advantages, but the Bureau’s selection criteria was that they had experience with the product, its availability, and that it met all the system requirements at the time. The Bureau named its implementation of BITBUS “BOMNET.”

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 Mbit/s. 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 1000-ft cable segment with a maximum of 16 nodes, and a communication speed of 375 kbit/s. The 1000-ft length of the cable segment, the number of nodes, and the speed are dictated by the BITBUS electrical specification.

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 multidrop 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. 2) 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 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. 2) 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

![BITBUS DATA LINK FRAME](image)

*Fig. 2. BITBUS protocol.*
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 acknowledgments 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 s). The 8044 also includes a small (2 kbyte) 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 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. 3 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 (Fig 4). 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.

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 (this is the length of the cable from the mining machine power center to the
The Bureau added BOM/NET, assorted sensors, and external computer systems to the control hut and the machine. Some of the sensors used on the mining machine are shown in Figs. 5 and 6. The sensors monitor the movements of various appendages, as well as key environmental systems. The data from the sensors are used for control and diagnostic purposes. BOM/NET as applied to the Joy 14CM is shown in Fig. 7. The bubbles in the figure are nodes in the network, and 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 the autonomous mining research and development system (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

Fig. 4. Picture of the Joy 14CM underground.

Fig. 5. Joy 14 cm appendage control sensors.

Shear elevation RVDT
Conveyor swing RVDT
Gathering head RVDT
Conveyor swing RVDT
Stabilizer clinometer
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.

**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. 2) 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 seconds 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 its target, it responds to AMREDS with a #IFC40000cr, which is a CECP. This is a final acknowledgment from node 1 that the conveyor reached its 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-ms delay to the network throughput, giving the network a predictable determinism. The delay adds up per number of nodes in the network mainly due to 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 ms. 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-ms, 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 intuition. In this mode the operator manipulates a bank of switches (Fig. 8) that corresponds to control functions for the Joy 14CM machine. The operator’s actions are echoed at the Joy 14CM. The operator verifies the results by watching the output of two machine-mounted cameras on two TV monitors housed in the control hut. Graphical displays of critical Joy 14CM parameters are also provided.

**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 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 (Fig. 9). The scripts can access navigation data to insure that the Joy 14CM stays on its preplanned path. 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.

Providing Problem-Free Power and Complete Electrical Isolation

Mine electrical power systems are characteristically unsuitable for operating computer hardware, especially when the mining machine is operating in a production situation. The 110 V ac supply on continuous mining machines have been observed to fluctuate as much as ±25%. Also, transients caused by lightning and inductive load switching can be as high as 2000 V and last up to 500 s. "Brown-out'' and "black-outs'' are common occurrences. The Bureau addressed these problems by using a heavy duty transient arresting device, and an uninterruptible power supply (UPS). The combination provided fluctuation-free power for the poorest mine power conditions.

Mine power systems not only affect the power supplied to the computer, but also can induce problems into the control, monitoring, and communication lines that attach to the computer. Hence, the control lines employ optically isolated relays, the sensors employ transformer isolation modules, and communication lines employ special transient arrestors and optical isolators. This combination of devices has worked very well because no failures have been documented in the respective system areas.

Providing Fail-Safe Shutdown if Failures Occur

In a mine production environment it is inevitable that equipment failures occur, and those failures will include the computer systems. This possibility must be provided for especially because one node has complete control of the mining machine. Both the software and the hardware can fail so both must be monitored. A "watchdog timer" scheme implemented by the Bureau consists of a software timer trigger and a power status signal, which feeds an external mining machine control power circuit. As long as the software task is operative and the computer has the proper power, the computer can control the mining machine. However, if either or both signals are absent, then the external "watchdog timer" lifts all of the power to the mining machine, rendering it inoperative. Also, if the network communication line is shorted or opened, the mining machine halts. Halting of the machine is the desired result when any failure occurs. Upon any failure, maintenance personnel are sent in to make repairs.

Potential Use

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.

References

[2] Vendor list: Computer Dynamics, 107 S. Main Street, Greer, SC 29651; Cincinnati Electronic Syst., 420 Wards Corner Rd, Loveland, OH 45140; Datem Ltd, 148 Colonnade Road, Nepean, Ontario, CANADA K2E 7R4; Micronetics, P.O. Box 347, Greendale, WI 53124; Datel, 11 Cabot Road, Mansfield, MA 02048.
[3] J.J. Sammarco, "Mining machine orientation control based on inertial, gravitational, and


[8] Graphics Node (No further details available at this time).

[9] NEC Powermate 386/20 AT computer. (No further details available at this time).

**Anatomy of a Magazine**

Here are some of the activities required to produce IEEE Control Systems Magazine.

**Chronology**

Currently, the Magazine is published bimonthly, with the first issue each February. Deadlines for published material vary, but are generally about four months before the issue date. Additional time is required for technical articles because at least two months are needed for review and another month is allowed for author revisions. It is possible for a technical article to appear in the Magazine seven months after it is submitted.

**Technical Articles**

Perhaps the most important activity of the Editor is to solicit interesting technical articles for the Magazine. The papers solicited for IEEE Control Systems Magazine should deal with control of something real, and they should contain appropriate words and figures rather than just equations and proofs. Examining conference proceedings allows the Editor to select articles of interest to the reader and permits selection from a wide range of topics.

Each year, the Editor looks through some 300 papers from the Conference on Decision and Control (CDC) and another 300 papers from the American Control Conference (ACC). Unfortunately, some good papers may be overlooked, but a personal solicitation letter goes to about a dozen papers from each conference. In the same way, the proceedings from annual conferences of two IEEE sister societies are examined to solicit papers from appropriate special issues that go to those societies. A special issue in cooperation with the IEEE Robotics and Automation Society is published in February, and an issue with the IEEE Systems, Man, and Cybernetics Society is published in August.

A second key activity of the Editor is overseeing evaluation of the technical articles. The Editor keeps one copy of the five copies submitted by the author and sends four to the appropriate Associate Editor. The Associate Editor keeps one copy and sends one copy to each of three selected reviewers. The reviewers are asked to return their evaluations and comments in four weeks, and the Associate Editor is asked to make a decision in six weeks so that the author can get an answer in two months. If the answer is "accept subject to revision," the author is given one month for revision. Each reviewer is sent a copy of all the reviews along with the letter of transmittal to the author. If extensive revision is required, the Associate Editor (sometimes with help from the reviewers) reexamines the revised manuscript.

**News and Other Departments**

Many department items are similar from year to year; therefore the time schedule can be determined by examining issues from the previous year. For example, reports from the Society Board of Governors Meeting in June (just before the ACC) appear in the October or December issue, and reports from the Board meeting in December (just before the CDC) appear in the following April or June issue. In general, the Editor solicits department items, looks through the submissions, and edits them to conform to the Magazine's style. Material submitted for departments should be sent at least four months before the desired issue date of the Magazine.

**Publication**

Materials accepted for publication are sent to Managing Editor Terri Schiesser at the IEEE Magazines Department, under the direction of Patricia Walker. Authors are asked to supply electronic files of their articles to the IEEE. The author supplied disks or email transmissions are then translated, edited, and formatted into galleys for author review. Authors read and make corrections on galley proofs, and return the proofs to IEEE.

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