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DISTRIBUTED COMMUNICATIONS AND CONTROL NETWORK FOR ROBOTIC MINING

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ABSTRACT

The application of robotics to coal mining machines is one approach the U.S. Bureau of Mines is pursuing to increase productivity while providing enhanced safety for the coal miner. Toward that end, a network composed of microcontrollers, computers, expert systems, real-time operating systems, and a variety of program languages are being integrated by the Bureau that will act as the backbone for intelligent machine operation.

Actual mining machines, including a few customized ones, have been given tele-robotic semi-autonomous capabilities by applying the described network. Control devices, intelligent sensors and computers onboard these machines are showing promise of achieving improved mining productivity and safety benefits. Current research using these machines involves navigation, multiple machine interaction, machine diagnostics, mineral detection, and graphical machine representation. Guidance sensors and systems employed include: sonar, laser rangers, gyroscopes, magnetometers, clinometers, and accelerometers.

This paper provides information on the Bureau's network of hardware/software and its implementation on mining machines. Anticipated coal production operations using the network are discussed. A parallelism is also drawn between the direction of present day underground coal mining research to how the lunar soil (regolith) may be mined. A conceptual lunar mining operation that employs a distributed communication and control network is detailed.

1. INTRODUCTION

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

Presently, the work is concentrating on the coal mine face area (coal extraction point). A typical face area is shown in figure 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.

An obvious approach to improve the safety of the workers is to remove them from the face and into a secure area. Remote-controlled machines are now available that at least get the person off the machine and away from some roof falls, but the worker is still exposed to hazardous situations by being in the face area. Increasing the efficiency of the coal production process can be addressed in a number of ways. The application of robotics, computer diagnostics, and machine redesigns will help.

The present focus of one Bureau research team, in response to the needs of safety and increased productivity, is to develop an autonomous coal extraction machine. The work involves numerous research areas [1-5] that are being investigated as logically and functionally distinct entities.

This paper describes the network that facilitates the interchanging of information between entities and also provides control of some of those entities. The architecture of the distributed network's hardware and software as applied to a few applications is described, as well as the machinery on which it is installed. Also, a hypothetical concept for lunar liquid oxygen (LOX) production is described and the network which could be used to control it is also discussed.

2. THE RESEARCH ENVIRONMENT

The Bureau has a mining equipment test facility (METF) at its Pittsburgh Research Center (PRC). A large building houses a few full-sized mining machines along with a large block of simulated coal (coalcrete). Figure 2 shows the inside of the building and the general layout of the research area. Shown in the center of the picture is a Joy 16CM[1] continuous mining machine which serves as the testbed for our experiments. The coalcrete is used for dynamic testing of mining machines under computer control.

3. THE JOY 16CM MINING MACHINE

The Joy 16CM is a continuous coal mining machine designed to operate underground. It is 16 ft wide, 4 ft high, 40 ft long, and weighs 50 tons. A control devices combination of electric and hydraulic systems run the various machine. The Bureau added a control computer that parallels the human control functions to the machine. Additionally, sensors were placed on all the machine appendages and environmental systems.

4. THE MINING MACHINE COMPUTER SYSTEM

A Bureau-designed onboard computer provides access to all sensors and provides complete control of the Joy 16 CM machine. Additionally application computers, both onboard and off-board the machine, provide for navigation, diagnostics, production planning and other activities. The backbone of this system is a real-time control network called Bitbus [6]. The Bureau's implementation of Bitbus, known as BOM/NET, consists of a collection of microcontroller boards that are configured for both stand-alone operation and as gateways to other computers.

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[1]Use of manufacturers names is for identification only and does not imply endorsement by the Bureau of Mines.

5. GENERAL NETWORK DESCRIPTION

Figure 3 shows the general layout of the network hardware as it is presently being used. The network was built to provide a method of tying together a variety of systems and subsystems so that they can communicate and interact with one another. Each system connected to the network can generally be classified as a sensor type, a control type, or a planner type. Additionally, each module is designed to be as intelligent and as self-reliant as possible. This, in effect, minimizes the amount of data that must be passed between modules, facilitating the highest level of real-time performance.

6. THE NETWORK OPERATING SYSTEM

A very efficient and compact operating system is used to manage all the resources of BOM/NET. It is called iDCX 51 [6] which is a real-time, multitasking operating system. Both iDCX 51 and the data link protocol are embedded in the firmware of every Bitbus card used in this network. iDCX 51 permits each node to have up to 8 concurrently-running, prioritized programs or tasks, and all can be interrupt driven.

7. THE NETWORK HARDWARE

Referring to figure 3, node 1 provides complete control and monitoring of the Joy 16CM mining machine. Built-in functions provides control of all of the machine appendages and control devices, as well as collection of sensor data. Node 2 is a microcontroller-based navigation system [2] that employs a gyroscope, an electronic compass, and clinometers. Node 3 is configured as a gateway to a Sun 3/60 computer. The Sun 3/60 computer is a workstation that is being used to develop a laser-based navigation system [1]. Node 4 is configured as a gateway to a Sun 3/160 computer. This workstation serves as a manual command center, a developmental platform for control programs and a graphical display device. Node 5 is configured as a gateway to a Symbolics 3670 computer that provides hydraulic system presentation using color graphics. Node 6 is configured as a gateway to a speaker-dependent voice recognition system [7]. Node 7 is a voice synthesizer [8] that provides messages for many system functions. Node 8 acts as a gateway to a specially constructed vehicle called a Locomotion Emulator (LE). The LE is a 3-wheeled, all-steer, all-drive mobile vehicle (see figure 4) which is software configurable and can emulate the motion and computer configured command set of most wheeled or tracked vehicles. Node (F) acts as the communication manager of the network.

8. RESEARCH SPINOFFS

Demonstration of the inherent capabilities of BOM/NET led to a request by another Bureau group for a customized remote control package for a new highwall mining system (HMS). The system was required for monitoring and remote control of a thin-seam continuous miner (TSCM) and a 76-m long multiple-unit continuous haulage (MUCH) conveying system. The MUCH system consists of 12 vehicles, each vehicle has autotracking abilities and features, integral chain conveyor, and four-wheel steering with two-wheel drive. An artist's drawing of the HMS is shown in figure 5. The HMS is controlled from a protected human-engineered operator station (HEOS) that remains outside of the coal seam being mined. The HMS features a laser-based guidance system, dual machine-mounted color TV cameras with dual HEOS-mounted video monitors, a complete remote control set for all system functions, bar graph sensor display boards, and a complete suite of TSCM-mounted sensors for machine position and diagnostics. Further details of the HMS can be found in the publications of reference [9].

9. A CONCEPTUAL DESIGN FOR A LUNAR MINING OPERATION

Overview

Experience in mining and mining methods has been accumulated for many different geological environments, terrains, deposit types, rock properties, depths, climates, and other factors that affect mining operations on earth. Additionally, experience is being gained in applying automation and robotics to machinery used for mining. Application of this experience to what has been learned about the lunar surface should enable us to generate designs for harvesting lunar resources that will be required to support lunar-based, lower earth orbit, and other space missions.

The design of a lunar mining operation will be based on a diverse list of fundamental considerations including at least the following items: (1) the product; (2) the volume of production; (3) the environment; (4) the machine/design; (5) maintenance/repair; (6) power requirements/power source; (7) human requirements; (8) processes involved; and (9) production coordination. All of the above considerations warrant intense evaluation and study well beyond the scope of this paper. Therefore, the major emphasis provided here will be the coordination of the mining operation via a communications and control network. The remaining items will be briefly discussed to form the whole concept.

The Product

Analyses of lunar rock and soil from six Apollo missions have identified mineral properties that can be used to supply many of the resources necessary to support space activities. The results have shown that the rocks and soil are rich in oxygen, silicon, and valuable metals such as iron and titanium [10]. Oxygen is the product of choice because of its use in fueling spacecraft. Oxygen makes up 6/7 of the mass of propellant utilized by cryogenic rockets [11]. Estimates vary, but on the average 1 pound of solid oxygen can be extracted from 135 pounds of lunar soil. The most predominant minerals in the lunar soil, containing oxygen are, olivine, pyroxene, and ilmenite. The reduction of these minerals to produce LOX will probably require a combination of processes like carbothermal extraction, electrostatic or magnetic separation, electrolysis, and liquification. Hydrogen, the second major ingredient of rocket fuel, could also be obtained from lunar dust, but it is very rare. Estimates show 50 to 200 ppm in the lunar regolith. Hydrogen recovery could be performed in conjunction with the production of oxygen using a thermal release process [12].

The Volume of Production of Oxygen

The amount of oxygen (O_2) that can be produced will be based on many factors, most of which are unknown at this point. However, we do know that to produce 40 pounds of O_2 per hour, it requires the processing of 5,400 pounds per hour of lunar soil (57.5 ft^3). Production volume will, of course, be dictated by demand, and supply will be limited by the efficiency of the production process.

The Environment

Information, supplied in one report [13] shows the lunar surface temperatures vary from +137° C in sunlight to -169° C at night or in a shadow, and variations can be as rapid as 174° C/min. The lunar day, as well as the lunar night, lasts for two weeks. The atmosphere on the moon consists primarily of solar wind gases such as hydrogen, helium, and neon, and is at a pressure of 10 (E-12) torr. Compared to the surface conditions, the subsurface is more stable due to the lunar regolith being such an excellent insulator. It maintains an unvarying thermal gradient. At 6 ft deep, the temperature is -17° C, at 8 ft it is -16° C, and at 100 ft it is estimated to be a constant 2° C.

Production Machines/Design

Lunar equipment design for soil extraction, transportation, and processing will require input from many disciplines. Tribiological considerations will be major due to an atmospheric pressure of 10 (E-12) torr. At that pressure only solid lubricants can be used for bearings and frictional surfaces. Problems like vacuum adhesion [14] will require unique solutions. Less energy and forces will be required to excavate soil and rock, due to 1/6 the gravity of earth. Countering that, however, may be the requirement of increased tractive forces necessary to counterbalance excavation by using energy-robbing anchoring mechanisms. Stresses in equipment due to light/shadow effects while a machine makes a turn in the sunlight will require special attention. As an example, a straight aluminum rod, half in sunlight and half in its own shadow, if a meter long on the underside, will be approximately 1.0375 meters long on the top, resulting in an appreciable warp. Perhaps a sun umbrella could minimize the problem. Night-time mining would also be an option.

The machinery designed for lunar mining should include the highest levels of automation and robotics that will require the least amount of human intervention. It should be multifunctional, and include enough redundancy to minimize system failures. A "smart wheel" concept, which has also been referred to as a Standardized Mobility Unit (SMU) described in reference [15] seems appropriate. An operation would consist of a number of SMU's. Each would be identical in size with standardized wheels. Each wheel would feature independent steering and suspension, and each could be engaged or disengaged, i.e., driving or free-wheeling. Coupling methods for each SMU would provide for mechanical, electrical, and communication conveyance, and each could be operated locally, remotely, and autonomously. Standardized attachment points on the SMU would permit attaching devices such as manipulator arms, tools, bins, conveyors, or crew transportation pods. Power could be onboard, supplied by fuel cells, or could come from some central power distribution point through other SMU's.

Maintenance/Repair

By design, the machinery used to produce LOX should be simple to maintain and highly reliable. Use of modular construction techniques and providing a high degree of component redundancy will facilitate both easy maintenance and could provide for continued operation even after multiple failures. As a result, the inventory of spare parts would also be minimal.

Power Requirements and Power Source

Full-scale oxygen production of the sort being described, will have a huge power requirement. A conservative estimate would be 100 kW. Power of this magnitude can best be supplied by a nuclear source at least in the beginning phases of production. Later, solar or maybe fuel cells using lunar hydrogen and oxygen could be developed to supply power.

Human Requirements

If a lunar mining operation becomes a reality, it will have to be supported by at least intermittent human supervision. A major concern of human occupation of the moon is the exposure to harmful radiation. The 5 rem/y exposure limit for earth-based radiation workers might be an appropriate standard for radiation protection. Reference [16] shows that adherence to this standard would make it necessary to bury a lunar habitat beneath several meters of lunar regolith and limit human activity on the lunar surface to "regular working hours", inside an enclosed vehicle. Occasional solar flares producing solar energetic particle events would also limit surface activity to within range of protective habitats. Radiation is only one human concern; numerous others will have to be addressed.

10. LOX PRODUCTION FACILITY

Using the cited references, combined with general mining concepts and application of a few unique ideas, a LOX production facility was conceived (figure 6). Emphasis was placed on keeping the human in a protected habitat, in a self-contained module placed in a lava tube. All mining and LOX processing would be totally automated and the human would act only as an observer with the power to prevent failures, correct improper operations, and initiate modifications in unprogrammed situations. Navigation in the pit would be based on a laser ranging technique using the corners of the pit as points of reference. The regolith extractor (RE) would be based on a couple of SMU's. The RE would follow a grid/cell production pattern as shown. The harvested regolith would be transferred by a multiple section conveyor train (MSCT) to the LOX processing plant. Refuse material would be transferred back to the pit by another MSCT. The two MSCT's would be composed of conveyor sections attached to and powered by the SMU's. Power for the RE and the MSCT's would be centrally supplied from the LOX processing plant, but backup power onboard each SMU would be provided.

11. PRODUCTION COORDINATION VIA A DISTRIBUTED ARCHITECTURE

The distributed architecture necessary for coordinating and controlling a LOX operation would be extensive. The system used would also have to withstand unusual environmental hazards such as temperature extremes and radiation. However, the system would not have to meet the standards required for providing life-support systems. Reliability of systems would be provided by parallel redundancy, cross-strapping,[2] and built in predictive failure techniques using expert systems. A multiple cabled network for interconnecting the SMU's would prevent a failure from interrupting communications between the other SMU's. The network would provide slave switches that would switch nodes between cables or isolate nodes out of the system. Network monitors and control computers would provide integrity through status polling, diagnostics, and control of operations. NASA has at least one patent application for such a network [17]. Each SMU in the network would contain a cluster of computers dedicated to specific tasks. The tasks would include at least a vehicle controller, position locator, obstacle avoidance, route planner, diagnostics, peripheral controller, and a communications handler. Vehicle control would be determined by onboard systems and by commands provided by an off-board production planner. The position locator could use onboard navigation sensors or could obtain its position from an off-board device. Expert systems embedded in hardware could perform continuous diagnostics and flag failures or impending failures to supervisory computers. A peripheral controller would permit control of devices attached externally to the SMU. The communications handler would provide for onboard, network or radio intercommunications.

The regolith processing plant would perform a variety of separation and oxygen extraction cycles. Control and operation would be autonomous and the same computer network used on the RE and MSCT would be used. Coordination of LOX production would primarily be provided from a central point where the human operators would oversee the process and provide input as needed.

12. ANALYSIS OF THE LUNAR MINING OPERATION

The described lunar mining operation was developed using the limited amount of lunar data that are available, and a small set of design considerations. Before a lunar mining operation becomes a reality, much more data must be obtained about the lunar surface. It is still unknown whether the Surveyor and Apollo sites are representative of the remainder of the lunar surface. The SMU's and peripheral devices described are elegant concepts but proof of performance must be verified in a simulated lunar environment. Many potential processes to reduce the lunar regolith to liquid oxygen have been conceived and some have been tested, but a method to identify design failings of full-scale production of oxygen employing these processes has not been established. Supervision of the production operation will undoubtably employ a distributed computer network architecture. The selection of devices used in a lunar mining operation should be based on a quantitative analysis of alternatives and priorities. Members of NASA's Automation and Technology Branch have written a computer program [18] that can provide an analysis of alternatives based on certain design criteria.

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[2] A construction technique that consists of connecting redundant components in such a manner that a single component failure will not cause a module failure.

13. CONCLUSIONS

The Bureau of Mines has integrated a distributed processing network, that enables a diverse collection of computers and intelligent sensor systems to intercommunicate and interact over a common data path using a simple protocol. The installation of the network on a mining machine used for research has accelerated the generation of intelligent navigation and control algorithms. The installation of the network on a mining machine used for production has demonstrated its real-time control capability. Each of the cited applications have shown that the distributed processing and control network (BOM/NET) has increased the reliability and the functionality of the system to which it has been attached.

Real-time performance and intercomputer communications are a must in any type of robotic system. Robotics will no doubt command a large role in a lunar mining operation and, therefore, some type of distributed communications and control system will be employed.

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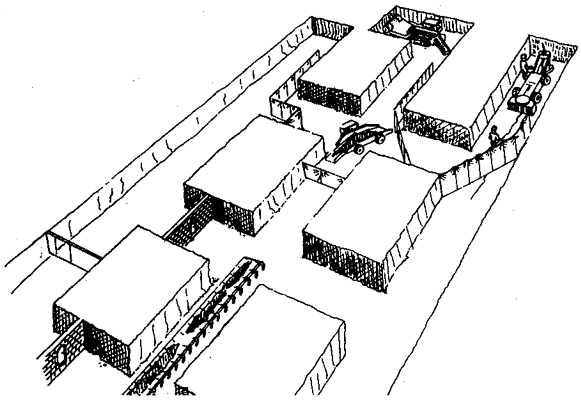

Figure 1. - Room and pillar face area.

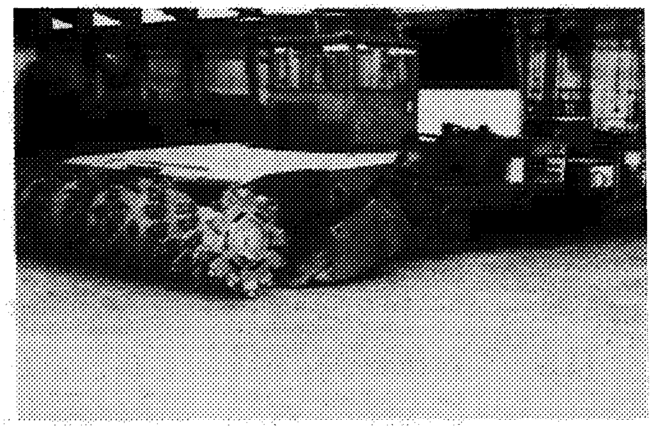

Figure 2. - Joy 16CM research area.

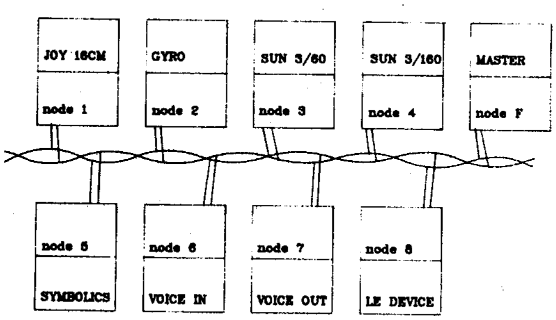

Figure 3. - Network layout.

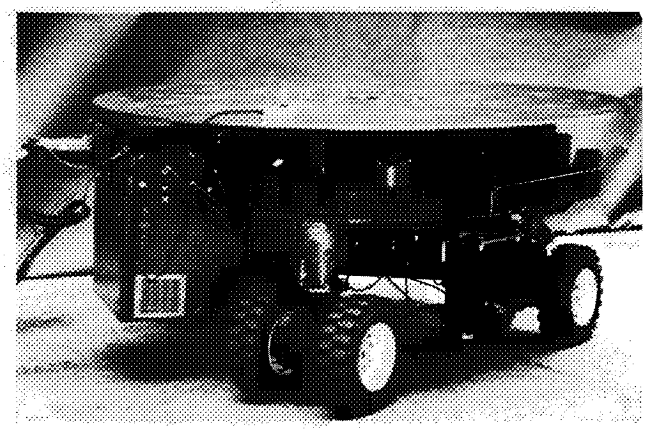

Figure 4. - Locomotion Emulator.

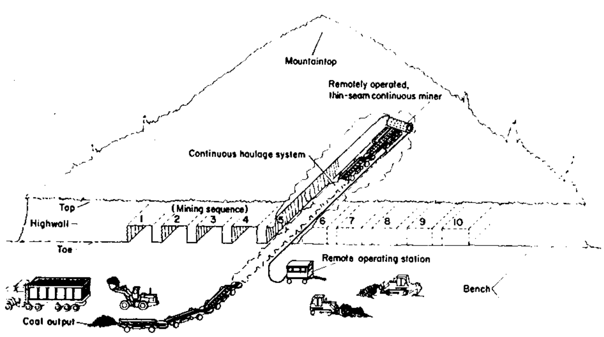

Figure 5. - Highwall mining system.

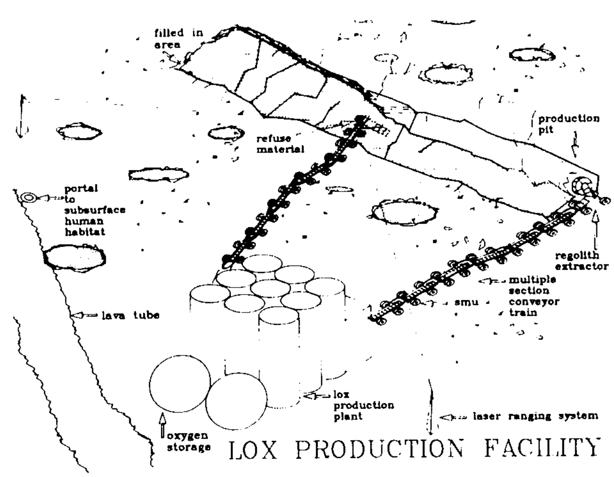

Figure 6. - Lox production facility.