INTERNATIONAL JOURNAL OF RESEARCH IN MECHANICAL, MECHATRONICS AND AUTOMOBILE ENGINEERING (IJRMMAE)
ISSN: 2454-1435 (Print) | 2454-1443 (online)
Volume 1 Issue 3, October – Dec. 2015 - www.ijrmmae.in – Pages 209-213

MINING ROBOTICS – A REVIEW

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ABSTRACT
Mining is the process of extracting mineral resources from the Earth for commercial value. It is an ancient human activity which can be traced back to Palaeolithic times (43 000 years ago), where for example the mineral hematite was mined to produce the red pigment ochre. The importance of many mined minerals is reflected in the names of the major milestones in human civilizations: the stone, copper, bronze, and iron ages. Much later coal provided the energy that was critical to the industrial revolution and still underpins modern society, creating 38% of world energy generation today. Ancient mines used human and later animal labor and broke rock using stone tools, heat, and water, and later iron tools. Today's mines are heavily mechanized with large diesel and electrically powered vehicles, and rock is broken with explosives or rock cutting machines

BACKGROUND

For the purposes of this chapter, mining may include minerals, coal, salts, gemstones, tar-sands, shale oil, and construction material, which we will refer to collectively as commodities. Commodities may be exposed at or close to the surface, or deep underground. They may be concentrated into seams or veins or evenly dispersed so that a significant amount of waste material must also be extracted and dealt with. Economic black coal is always found as a monolithic seam, a consequence of the manner in which it is formed by vegetable matter accumulating on the floor of ancient seas and lakes. Gold can be evenly disseminated or found in seams of quartz that was long ago forced through fissures in the surrounding rock mass. Some mineral deposits such as Canada's Sudbury nickel, are speculated to have come from meteorite impact so the resource is distributed around what seems to be an extremely large crater. The extraction of petroleum and natural gas is not generally considered as mining and will not be discussed in this chapter. Mining may occur on land, below the surface, on the ocean floor, and in the future in space.

The first row distinguishes the different broad class of material that is extracted. Metalliferous refers to metal bearing ores. Coal is found as black coal, a hard black *rock-like* material, or softer wetter brown coal. Quarrying refers to the extraction of stone, gravel or sand which is used as a building material or for use in concrete and road base. The second row in the taxonomy differentiates the location of the material. Underground mining methods are more expensive but are used for deeper material and this requires excavation of shafts and tunnels. Mining of deep ocean trench, black smoker sulphide resources is just beginning.

The grade, or mineral concentration, of these resources is very high by terrestrial standards and mining methods are just being developed. The cost of reaching these resources is extremely high, and concern about fragile underwater ecosystems has acted as a brake on their exploitation. The third row differentiates the physical state of the resource. Free digging materials such as bauxite, mineral sands, oil shales or salt can be simply *scooped up*. Harder materials need to be fragmented, typically by placing explosives in holes drilled into the ore. Rock cutting methods are sometimes used but this is applicable to only a small range of materials and the cost of cutting tools and power to drive the cutting process are often limiting factors. Development in this area is driven primarily by advances in hard materials for the cutting teeth. A marked difference between current techniques for free-digging materials such as coal and hard rock (metalliferous) mining is the continuous nature of the former compared to the cyclical nature of the latter. Soft material can be extracted and conveyed to the surface continuously, whereas in the case of hard rock mining the process is generally not continuous, requiring breakage through blasting then loading and hauling on a cyclic basis.

ROBOTICS IN MINING

In this chapter we distinguish between several related technologies: automation, teleoperation and robotics. We define automation as conventional computer- or programmable logic controller (PLC)-based control systems, and teleoperation as remote control of equipment by an operator using information provided by video cameras and graphical display of machine state. This section discusses various aspects related to the introduction of robotics in mining.

DIFFERENCES FROM FACTORY ROBOTICS

Existing mining equipment is typically hydraulically actuated and either diesel or electrically powered. Work tools or end-effectors are often located at some distance from the operator and power source. Loads and masses are high and the equipment is expensive. In robotic terms, equipment is heavy, compliant andmobile. Localization, particularly absolute localization, is extremely difficult. The operating environment may also be extreme, in terms of high temperatures, salty and acidic water, and exposure to rockfall and robust treatment. The equipment may also be hazardous to humans, and in the transition period before fully robotic mines, the issue of human safety is paramount. Current prototype mining robots are essentially converted mining machines, but over time they will evolve to be purpose-built robots.

ACCEPTANCE BY MINE OWNERS

To date, there have been few successful and practical robotic applications that have met the difficult operational requirements. There are some good reasons for this. Unlike traditional areas that have high uptake of robotics/automation such as factories and even mineral processing plants, the mining environment is not stable and is in a constant state of evolution. Machines and people must be adaptive and flexible and engage the natural terrain where they find it. Mining environments are difficult to alter to suit the easy application of automated machines. The design and configuration of factory and process machinery can easily be optimized and integrated into a well-performing and stable system. Before finance can be raised to establish a mine, the resource needs to be well defined and valued. This is essentially a geoscience-intensive statistical process resulting in some uncertainty. This may leave little tolerance to accept risk in the downstream activities such as mine design, construction, and equipment selection which are predominantly engineering focused.

Mine designers and ultimately investors like to use data and experience from existing successful operations. Therefore, any introduction of technology, including new mining methods is likely to be incremental, evolutionary, and undertaken with minimal disruption to existing production. Many in the mining industry have little familiarity with robotics or its potential. Mining engineering is a combination of mechanical engineering, geomechanics, geology, finance, and management. It is critical that other disciplines work closely with production-focused mining engineering staff so that the technology will be fit for purpose and/or the uptake will not be inhibited through a lack of understanding of business needs. Significant progress is often made by adapting technology developed for other markets and disciplines.

THE NEED FOR INTEGRATION

When a mine is in operation, there can be many unexpected conditions that present challenges to conventional robots that excel in well-controlled environments. The inability to manage exceptions will usually negate any superior performance that might be expected based on operation under controlled conditions. Robotic machines must be integrated with manual operations and their effects on up- and downstream processes must be properly considered, for example, if an automated machine requires an isolated area for safety reasons, and the same area requires regular or periodic access by people, then the benefits may be lost. To capture the benefits, other mining processes need to be modified to suit and a *systems* approach is recommended. Remote control is often a good first step towards automation. The use of remote control either within line of sight or with the aid of video cameras/sensors (teleoperation) is now accepted by the mining industry, although it has yet to achieve market saturation.

At the time of writing, a range of existing machines are being converted to *robots* through the application of automation technologies. Most notably these include high wall mining machines, load haul dump vehicles (LHDs), rock drills, and haulage trucks. There are few suppliers of this specialized equipment and they are experiencing significant demand beyond their production capability. Robotic conversion of draglines and coal shearers is now possible and prototype systems are being installed. New concept machines, such as for the robotic installation of ground support and explosives, are at prototype stage or undergoing early field trials. New mining methods that are designed from the outset for robotic machines are currently on the drawing board waiting for finance and trials. The wide diversity of mining operations, methods, and environments will also be discussed because these affect the selection, design, and limitations of robotic applications.

PRODUCTIVITY

Productivity gains from consistency of operation, rather than an increase in basic production rates, is a priority. Because of the inability of current automated or robotic mining systems to match the sensing and control functions of operators, such systems are unlikely to match the peak performance of the best operators. However the strength of automation systems is their ability to maintain consistent equipment operation over extended periods of time. In an essentially continuous process this brings real benefits.

Moreover, equipment operation can be constrained to always lie within performance bounds, conferring benefits in enhanced equipment reliability and improved product quality translating to availability and thence to productivity. The largely batch nature of metalliferous mining and the time taken to change shifts often provides an opportunity to automate equipment so that it operates continuously duringmeal breaks and shift changes. Typically, two to three hours can be saved each shift in this way, especially if machines can be controlled from a centrally located control room. Access to the machine can then be limited to regular servicing or relocation. Hot-seat changeover is also used to address this issue, although this often results in increased labor costs and longer or overlapping shifts. In the case of LHDs, improved productivity of 20% has been experienced through automation.

HEALTH AND SAFETY

When considering safety, it is self-evident that there are potential benefits if people can be removed from the hazardous environments near a mining face or equipment. Here, injuries from explosive atmospheres, noise, dust, rockfalls, and moving equipment are commonplace. In China, there have been more than 5000 fatalities per year in the coal mining industry, although the numbers are falling steadily. Further examination of this data identifies two categories of fatal injury that are significantly higher than all other categories: *vehicles or mobile plant* (31%) and *slides, cave-ins or rockfalls* (25%). When some of the other equipment-related incidents involving entrapment or machine faults are included, the *vehicle and mobile plant* category increased to approximately 36% of mining deaths over that period. The third most significant category relates to *falls, slips, and trips* (10.5%). Similar category distributions were found in the US mining and quarrying industry (National Institute for Occupational Health and Safety (NIOSH) statistics).

It is obvious that people cannot be hurt bymobile equipment if they are not close by. Hence removal of operators from the area using robotic technology with compatible procedural controls is a viable solution. In both coal and metalliferous underground mining, access tunnels must be supported by one or more methods including rock bolts, sprayed concrete, and steel mesh. There is always a period of time and location where ground support has not been installed following blasting or cutting and there is a risk of rockfall. Installation of ground support involves manual and mechanized activities and is a hazardous task. According to *Potvin* et al. there has been a significant reduction in injuries from metalliferous mine rockfalls since 1998. From Potvin's report, mining procedures and training have played a significant role in the reduction. However, the majority of rockfall deaths still occur in access tunnels (drives) less than 10m from an active mining face. Two-thirds of these deaths occurred during the installation of ground support or explosives charging. Again the logical way of reducing or avoiding fatalities and injuries is by removal of operators from the immediate vicinity where possible.

CONCLUSION

Today, mining remains hard and hazardous work with a wide scope for the application of robotics. The main drivers are the need for greater productivity and improved health and safety for mine personnel. Mining robots differ considerably from traditional factory robots

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in that the mining environment is ever changing, that is, the purpose of mining, and the machines are typically hydraulically actuated, and are often diesel powered. These challenges have meant that robotics has not been rapidly adopted by the mining industry to date, but it is clear that the mining industry will have to adopt more automation, and with it robotics, to further significantly improve productivity and safety as traditional methods such as staff training, improved work practices, and larger and improved machine design are providing diminishing returns.

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