49. Mining Robotics

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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 (Fig. 49.1).

Mining remains hard and hazardous work and the scope for the application of robotics is very high. Mining requires the handling of enormous quantities of material in a cost-effective and safe manner. High operational costs, the need for greater productivity and improved health and safety outcomes are powerful drivers for robotics. Existing approaches to improving productivity and safety through training, work practices, and larger and improved machine design are providing diminishing returns. The industry is close now to a tipping point where robotics and automation will provide the next step change in productivity and safety. A review of the global status of robotics in operating mines as of 2006 can be obtained from [49.1].

49.1 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

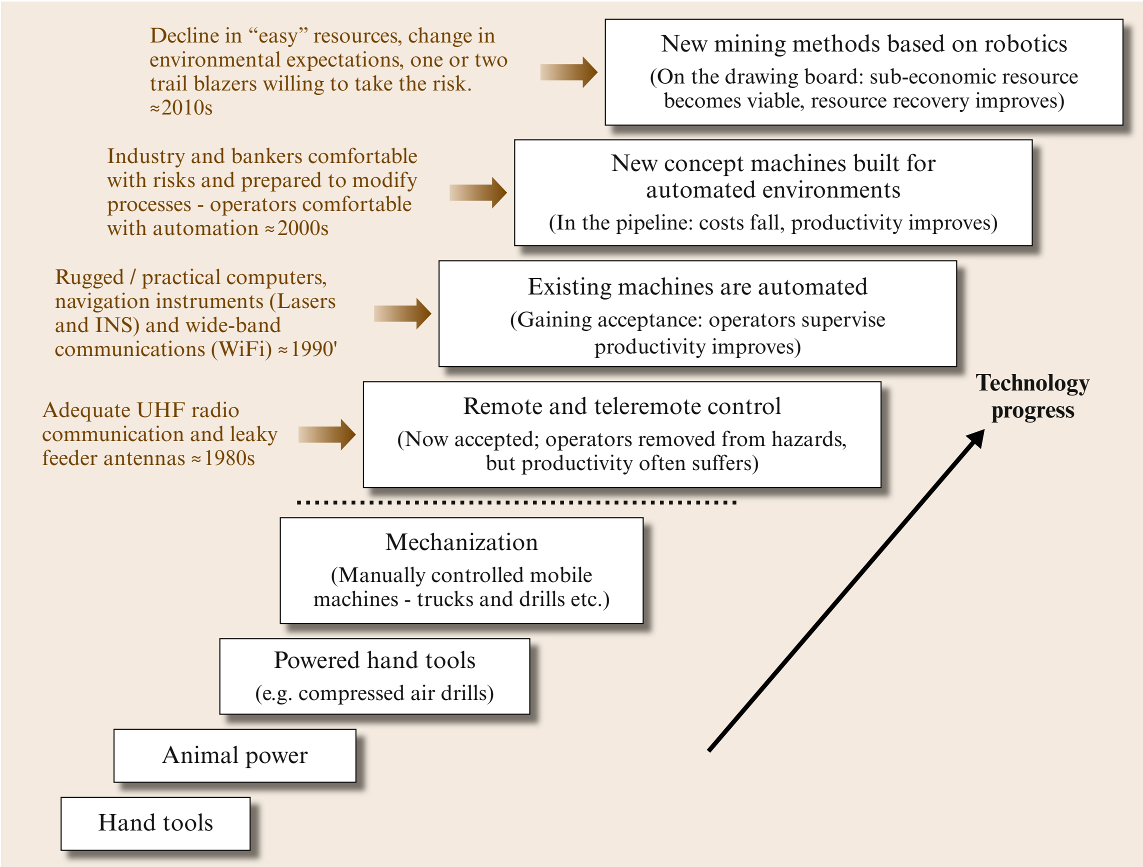

Fig. 49.1 Evolution of mining technology

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

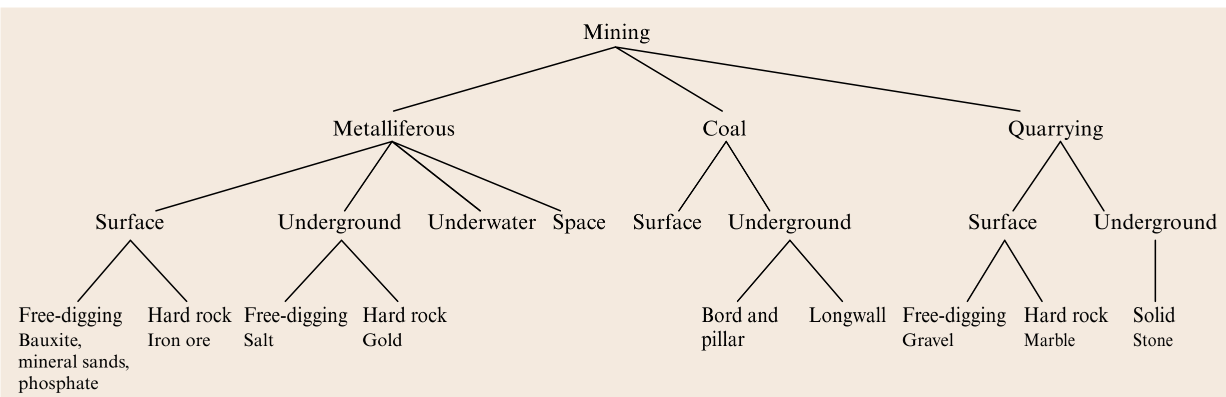

Fig. 49.2 A taxonomy of mining

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. A taxonomy of mining is presented in Fig. 49.2 as a framework for discussion. 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. Those on the surface of the Earth are extracted using large open-pit operations such as shown in Fig. 49.3. 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.

Fig. 49.3 An open cut coal mine with a dragline excavator (US Bureau of Land Management, Washington)

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.

49.1.1 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 and mobile. 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 highwall 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 (see, for example, Sects. 49.2.3 and 49.3.3) 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 during meal 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. Figure 49.4 shows the declining number of fatalities in the Australian mining industry from statistics published by the Minerals Council of Australia (MCA). 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 by mobile 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. [49.2] 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.

In order to make a significant further reduction in the number of mining fatalities and injuries without changing mining methods, the following areas need to be addressed as a priority with the introduction of robotic technology and proximity protection:

- Mobile equipment (LHDs, trucks, longwall equipment)
- ground support installation processes (including scaling and coal mine roadway development)

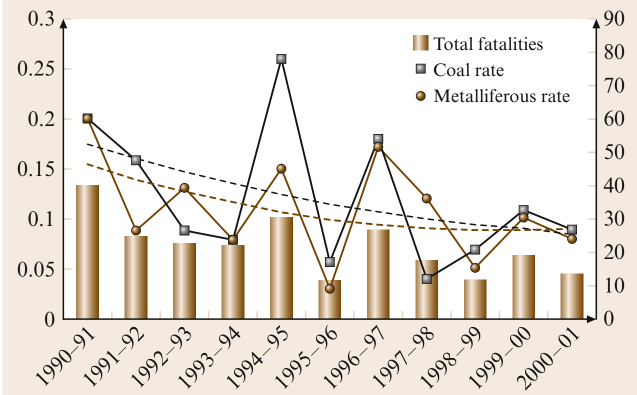

Fig. 49.4 History of fatalities in the Australian mining industry. *Left x*-axis is Fatalities per 1M man hours. *Right x*-axis is number of fatalities

- explosive placement
- rock drilling

It also needs to be acknowledged that some early introduction of close-range remote control and automation of existing mining equipment has actually resulted in deaths and injury. This was largely caused by a heavy reliance on procedural controls to maintain isolation from people. Operators were killed or injured by accidentally running over themselves or being caught in machines during maintenance. Poor design of control systems and interlocks may also have contributed to these incidences and has led to the development of industry standards. Failsafe engineering controls are critical to any robotic installation.

Acceptance by Miners

Despite the clear health and safety benefits there are perceptions in the workplace that these technologies will impact adversely on job security. The effect of this should not be underestimated but it can be managed. Consequently the current thrust of robotics and automation development in mining is to employ these systems to remove operators from direct roles in the most hazardous operational areas to safe-area supervisory and backup involvement. The robotics challenge is to develop the sensors necessary to replace the functions currently carried out by operators in the hostile operating environment, making their work easier.

There are many undesirable, monotonous, and hazardous tasks that can be addressed as a priority with general acceptance of the workforce if correctly introduced. Removing people from these activities to a role that involves supervision of a process instead of moment-by-moment operation will generally be well received by operators because it makes their work easier and safer. Robotics also enables a reduction in the mining workforce as productivity improves and this can cause resentment in some mining communities. This can be managed through natural attrition as the workforce ages and people are less inclined to seek employment in the industry. Over the longer term the skill base will change and new jobs will be created in knowledge-intensive areas associated with development and maintenance of robotic equipment. In Western countries with ageing populations, the shortage of skilled workers willing to live the hard and often remote lifestyle will drive robotics. Robotic mining could also keep mines open longer when it becomes uneconomic to mine using existing methods, mirroring the effect observed in the automotive industry where robotics has kept factories open rather than displacing workers.

49.2 Metalliferous Mining

For the purpose of this chapter, *metalliferous* is defined as all mined materials apart from coal, oil, and gas; for example, targeted materials may include, copper, lead, zinc, silver, gold, diamonds, iron, and aluminium. Several mining methods are used to recover metalliferous ore and references can be consulted for more detail about each [49.3–5]. Mining methods can be broadly categorized into surface and underground. Variations on the methods relate to the type of ore body or rock rather than the commodity or mineral they hold. For example, components of interest can be *disseminated*, that is distributed relatively evenly through a large volume of terrain. Here the boundaries of the ore body must be defined by the economics of mining. Such ore bodies are typically extracted using *mass mining* techniques. Ore can also be distributed in veins or tabular shapes ranging from a few centimeters to many meters thick. The boundaries of these ore bodies are typically defined by geology and they favor methods that are more selective, especially for underground mining.

Ore types can also be defined by hardness and the stability of the rock mass. Hard-rock ores usually require *drilling and blasting*. In some circumstances they can be made to cave-in if a large enough slot of rock is removed from below the volume of ore. Unconsolidated materials such as phosphate, salt, mineral sands, and bauxite are usually mined using excavators, rippers, shovels, and even dredges. Little or no explosives are used except where the ore is capped by hard, barren rock. These ore bodies are free digging and often alluvial in origin. Mineral sand is often mined using dredgers that float on an artificially created pond in the mineral zone. Sand is sucked up by a dredge and pumped to a processing plant. Another example of alluvial ore is presented by surf-zone marine deposits of diamonds which are located off the southern coast of Africa. Here, the heaver diamonds are separated from sand through wave action and they become become trapped in rock crevasses under the surf zone of a beach. Such deposits are mined using what is essentially a giant vacuum cleaner.

The following discussion of mining methods and infrastructure is made with the emphasis on aspects that are important for the design and application of robotics.

49.2.1 Underground Hard-Rock Metalliferous

The cost of underground mining can be between two and ten times greater than for surface mining. Therefore ore needs to be relatively rich to be economically viable for underground mining.

With some exceptions, metalliferous mining is a batch process involving a sequence of physical operations including:

- exploratory drilling
- geological and geotechnical mapping
- developing access roadways or tunnels (development)
- drilling and blasting of areas containing the ore (*stopes*)
- extraction and haulage of the broken ore
- back fill of extracted zones and rehabilitation

There are a large variety of different metalliferous mining methods that will weigh these separate process steps differently. Each has different opportunities for automation and robotics. Metalliferous mining has a significant reliance on explosives. However, new rock cutting technology is now emerging that will see a shift away from explosives, at least in the development of access roadways and for some surface mining [49.6]. Rock cutting applications will benefit from a high level of robotic control. In metalliferous mining there is a strong emphasis on total extraction of the resource, which often means that voids left by mining must be filled to ensure geological stability.

Figure 49.5 shows one example of an underground mine layout. Here, the mine has progressed from a surface mine to an underground mine as the easily available ore is depleted (e.g., the Kiruna mine in Sweden). In some cases, underground mines can also evolve into surface mines (e.g., the Kalgoorlie Consolidated Gold Mine in Australia).

Layout and Environment

Access to underground is either by a declining tunnel (decline) or shaft or sometimes both. A decline is a descending tunnel with a typical gradient of 1:7 which is also known as a ramp. Cross-sectional dimensions are typically between 5 m and 6 m and the road surfaces consist of compacted gravel, often mixed with finer material such as tailings to assist with consolidation. Road maintenance is a critical task that significantly affects the productivity of heavy vehicles. The Kiruna iron mine in Sweden is an exception because it has a bitumen decline roadway that is suitable for normal highway vehicles. A typical decline will consist of a series of straight sections between 200 m and 400 m long which are joined with a relatively tight 180° spiral turn to keep the tunnel in close proximity to the ore body. In some mines the decline is a continuous spiral for its whole length. Exits are placed periodically to give access to mine working levels, which consist of a network of tunnels. Tunnels are often called *drives* where they run roughly inline with the ore body and *crosscuts* where they cut across the ore body. The terminology is not strictly defined. Usually the roadways are one-way and contain periodic passing bays. The traffic is mixed, with light four-wheel-drive (4WD) service or utility vehicles operating together with large haul trucks that may have a gross vehicle mass of up to 110 t.

Virgin rock temperatures can reach 80°C, so operating areas including stopes are ventilated using air pumped from the surface. Sometimes air must be cooled and this is usually done near the operating areas using water that has been chilled at the surface and piped underground. Ventilation circuits are well managed and monitored to ensure operating areas are not downstream of any dusty, radioactive or fume-laden areas. This represents a significant cost which can be mitigated through the use of robotics that can operate in poorer quality atmospheres.

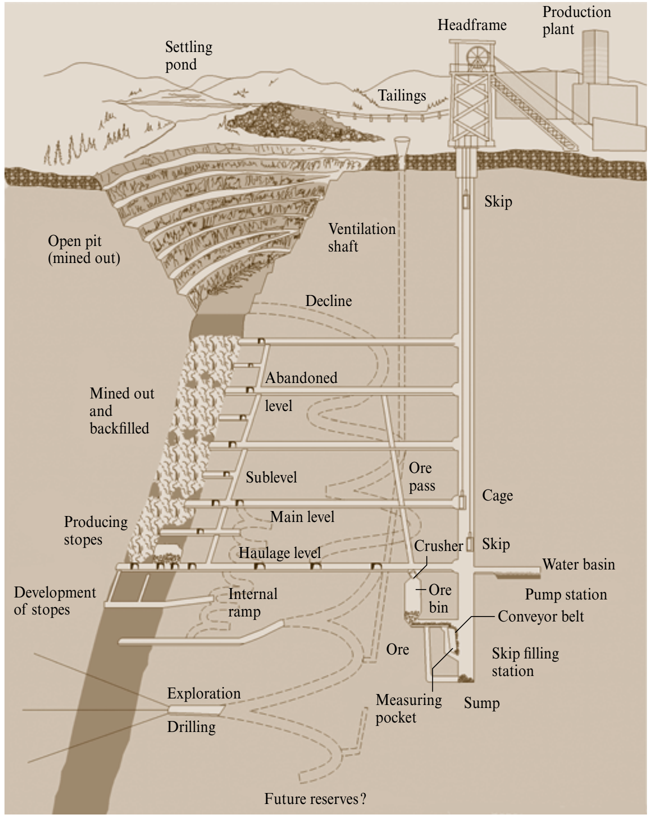

Fig. 49.5 Typical hardrock mine layout also showing transition between surface and underground mining [49.5]

Often mine workings intersect aquifers, giving rise to wet areas that must be drained. Mine water is often more salty than sea water and can also be extremely acidic. Electronic enclosures must be well sealed or drained and sometimes cooled. Developers also need to be aware that enclosures that are sealed in humid conditions may experience internal condensation if subsequently exposed to cooler conditions.

Block Cave Mines

The block cave underground mining method (Fig. 49.6) is the lowest cost underground method because once in production, the rock collapses and fragments under its own weight [49.5]. This minimizes the amount of explosives, equipment, and unit operations. Typically the ore bodies are large, disseminated, highly fractured or with low-tensile-strength rock. They may take a num-

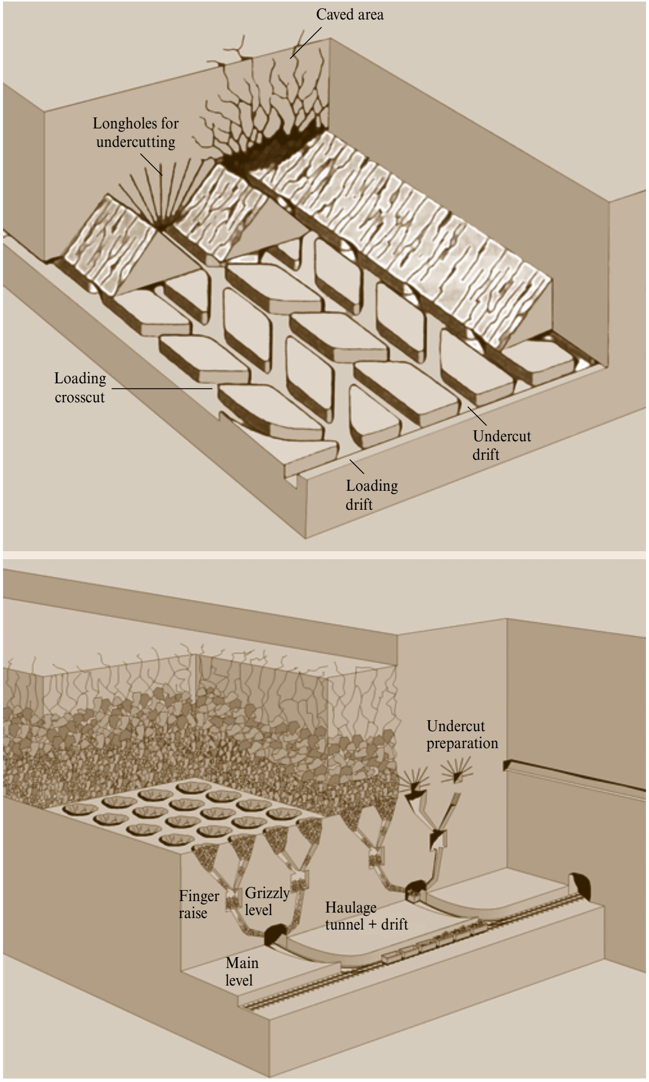

Fig. 49.6 Typical block cave underground mine

ber of years to extract, so a high level of infrastructure can be justified. This method approaches a continuous operation and is well suited to automation and robotics.

To create the cave, a large horizontal slab of ore called an *undercut* is removed at the base of the ore. The virgin rock can then no longer support itself and it caves. The broken ore *flows* downward and continues to fracture until it reaches a series of draw points which are linked to a tunnel network. Underground loaders (LHDs) pick up the ore from the draw point and take it to an underground crusher. There are several activities in block caving that may be suitable for robotics are

- automated loading and haulage
- ore hang-up clearance (including blasting)
- survey and inspection
- secondary rock breakage to clear large rocks

Stoping and Sublevel Caving

There are several other commonly used mining methods that have unique characteristics that differentiate them from a mining engineering perspective. However, for the application of robotics, they can be grouped together because they share similar challenges and equipment. These methods include:

- room and pillar
- narrow vein
- vertical crater retreat
- sublevel caving
- sublevel open stoping
- cut and fill

A classic example of a sublevel stope method is shown in Fig. 49.7. Examples of the other methods can be found in [49.3–5].

For these methods, access is gained to the ore body at various levels and the ore is fragmented, either entirely by drill-and-blast or in combination with caving (sublevel caving). These methods involve drilling holes for explosives and loading the explosives. Unlike block caving, these other mining methods are highly mobile, infrastructure is short term, congestion is heavy, and through traffic is common in the active areas. Careful consideration is required for isolation of any robot from manual traffic.

Activities similar to those mentioned for block caving are also suitable for robotic application with the addition of production and development drilling and ground support. For these mining methods there is a significant amount of tunnel (roadway) development, which is often a rate-determining step. The activities involved are all undertaken close to an active face and are therefore hazardous. This is a cyclic process with different heavy equipment continually deployed and replaced as the tunnel progresses.

Communication Infrastructure

Underground radio communication is challenging because of the wide variation in rock conductivity and the geometry of mine voids. Radio communication propagates with high attenuation through tunnels and voids and is significantly affected by vehicles and steel infrastructure. Currently the most common form of communication remains very high-frequency (VHF)/ultrahigh-frequency (UHF) radio which is propagated through *leaky feeder* coaxial antennas throughout the mine workings. VHF/UHF radio is used mainly for voice but also for serial data communications. For equipment teleoperation, UHF systems can also carry analog video on amplitude-modulated (AM) frequencies. Frequency-modulated (FM) video is rare because of the cost and the unusual effects caused by the highly dispersive nature of the mine terrain. If an unfortunate choice of wavelength is made, the tunnels and voids may act as waveguides and filters. This produces a complex and unstable performance for both AM and FM that can result in signal strength variation of 60 dB over tens of centimeters and significant interference from vehicles and other infrastructure.

With the relatively recent evolution of Ethernet and WiFi technology [49.7], such systems are gaining popularity and will soon be common. WiFi systems are now in common use by advanced mines and they usually include a fibre-optic trunk link from the surface to distributed access points underground. Because of the Ethernet protocol, radio propagation anomalies result in reduced and variable data rates and communication is less deterministic compared with analog communication. This variable and significant latency means that caution is required when using WiFi for control and alternate and independent safety systems are thus required. Radio transmitters are usually power limited or are otherwise isolated to avoid accidental ignition of detonators and other explosives. WiFi systems suitable for safety-critical control applications are emerging.

Through-rock radio communication is also available but it can only support data rates of tens of characters per minute in one direction (base to field). This mode of communication modulates low-frequency electromagnetic fields (a few kHz) generated from a long loop antenna located near or around production areas. The antennas carry high current at low voltage and communication shadows often exist near highly conductive ore. This communication mode can be used for issuing simple messages to personnel or simple control commands (off/on) to equipment. New technology for bidirectional through-the-rock communication is under development.

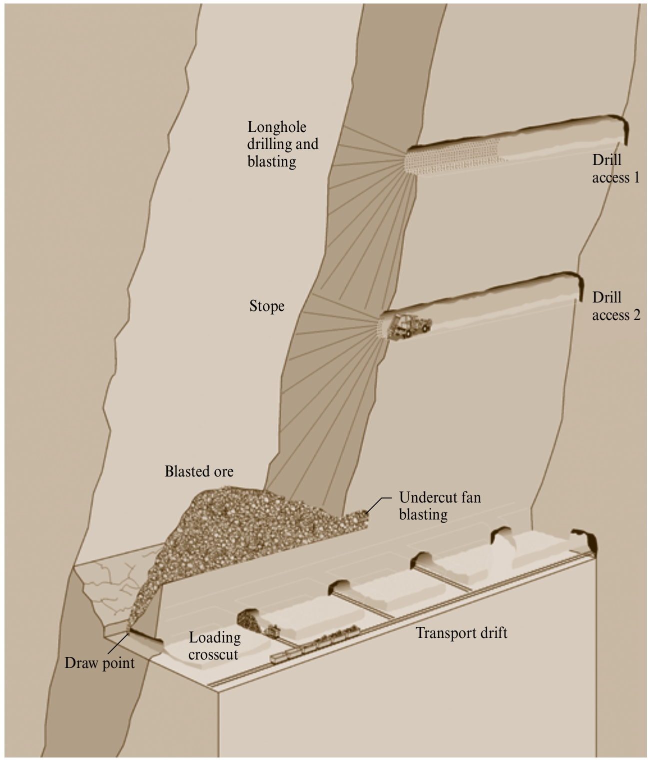

Fig. 49.7 Typical underground mining method called *sub-level stoping* (after Atlas Copco, www.AtlasCopco.com.au)

49.2.2 Scope for Robotics

This section will review aspects of underground metalliferous mining with a focus on the opportunity for, or impact on, robotics and automation.

Underground Transport

In all types of underground metalliferous mining, material must be moved from where it is mined to the surface. The movement of the material can be achieved using either conveyors, haulage vehicles or hoisted bins (*skips*). Conveyors and hoists have been largely automated using factory automation technologies.

Mobile vehicles are used to carry ore out of the mine along the declines, or to move ore from the face to loading points underground. Underground haul trucks are typically diesel powered and ascend at about 6–10 km/h, fully laden, and descend at about 20 km/h. Electric haul trucks are rarer and use pantographs to tap overhead power and are usually faster than diesel trucks, ascending at 18 km/h and descending at 24 km/h. Mobile haulage vehicles are normally used where a high

Fig. 49.8 A load haul dump (LHD) vehicle

level of flexibility is required and in particular at a mining face.

For almost all underground metalliferous mining, load-haul-dump (LHD) vehicles are used in the ore transport process. LHDs (Fig. 49.8) are configured like front-end-loaders with a large bucket but are articulated so that they can manoeuvre in relatively small spaces and through tight corners. The vehicles are *trammed* between the pick-up and dump points, which could either be a temporary stock pile, crusher, chute, shaft or haul truck. LHDs are rarely used to carry material for a distance beyond 600 m. Their maximum speed is approximately 20 km/h and they may have a clearance of less than 1 m to the tunnel wall either side. This is a tedious and hazardous task for manual operation. These vehicles can be diesel or electrically (via a trailing cable and onboard winder) powered.

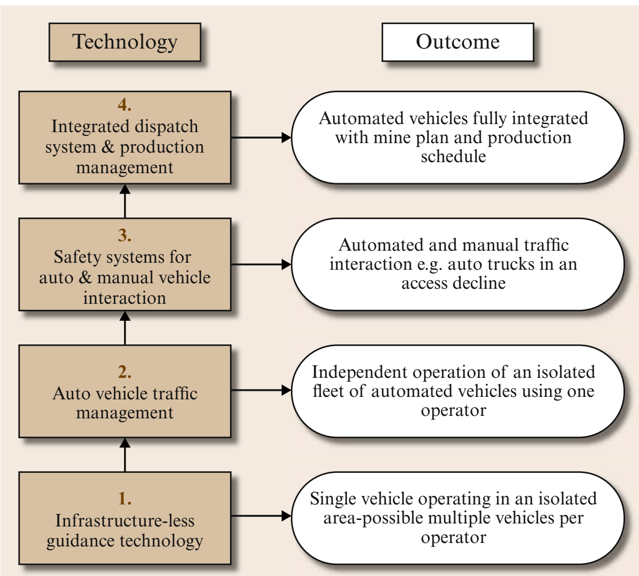

Fig. 49.9 The evolution of automated mining vehicle technology and the outcomes that could flow from each stage

The two obvious motivations for automating haulage vehicles are improved efficiency and safety. Improved efficiency can result from reducing labor costs, increasing operating duty, reducing wear and hence maintenance costs. Automation can be approached in a staged manner with each level of sophistication bringing benefits as shown in Fig. 49.9. The operation of LHDs is hazardous because the vehicle must venture into areas that are potentially unstable with a relatively high chance of rockfall. Traditionally LHDs are manually operated for the tramming cycle but operated by line-of-sight remote control while they operate in hazardous areas. Regularly changing the operating mode is time consuming and hazardous. Accidents have occurred where an operator has been crushed by the LHD as it returns from the stope by remote control. To avoid this risk, many mines now use teleoperation for the entire tramming cycle [49.8, 9]. However, this typically leads to slower tramming times than if the operator was onboard, which is due to the reduced perception and lack of feedback to operators that naturally occur when they are no longer on the vehicle. Hence, onboard vehicle navigation is the obvious solution to remove the operator from the hazard and maintain high-tramming speeds and productivity.

The automation of LHDs has been investigated by a number of researchers over the past two decades. Early systems used buried wires in concrete roadways as guidance infrastructure for LHDs [49.10]. However, concrete roadways are not common in metal mining operations and so this solution is of limited use. A common approach was to use an optical marker placed on the center line of the roof along the length of the tunnel. An upwards-facing camera was then used to track the lights and estimate the offset of the vehicle, which was fed into a steering controller. Early systems used either a painted white line [49.11] or retroreflective tape [49.12, 13]. Another system used a row of lights suspended from the centerline of the tunnel roof [49.14, 15].

Following painted lines, lines of retroreflective tape, lines of lights or wires buried in the ground has its limitations. The lack of longitudinal information (along track data) means that the speed of the LHD must remain low as the vehicle does not know when a corner is coming up. Solutions to this are to provide additional means of measuring along-track position, which could be odometry and some other absolute system such as radiofrequency identification (RFID) tags to correct the drift of the odometry.

The availability of the two-dimensional (2-D) laser scanner in the mid to late 1990s saw the development of new-style LHD guidance systems. Some of these systems worked by using reflective markers placed along the mine walls at regular intervals (tens of metres) [49.16]. The LHD localized itself using a map of the beacons and the observed range and bearing readings to the beacons as observed by a 2-D laser scanner. This data was fused with odometry information and inertial data (such as heading rate and acceleration). Another system used the detected free space ahead of the vehicle, as determined by a 2-D laser scanner to reactively steer the vehicle [49.17]. This system also used the topology of the mine, again as determined by the 2-D laser scanner data, to localize the vehicle for high-level navigation purposes such as speed setting, turn decision making at intersections, etc. This approach was successfully demonstrated in a production mine in mid-1998, was subsequently commercialized and is now available as a product. Other approaches to feature-based localization underground are described in [49.18, 19]. Automated tramming systems for LHDs area availably commercially from Tamrock, Caterpillar and Atlas Copco and market uptake is growing rapidly [49.1].

Traffic control is another important issue particularly in *mixed fleets* of human-driven and robotic vehicles. Currently each mine vehicle is equipped with VHF/UHF radio and local communication procedures are adopted to manage traffic. In some mines a decline is divided into segments or *blocks* and traffic lights (block lights) are used to indicate that a segment is occupied. A set of rules is used to give priority to ascending vehicles and heavy vehicles. A common control for autonomous vehicles is segregation of autonomous and manual equipment operations through the establishment of safety barriers to exclude people from the operational area. However these barriers are quite extensive and difficult to maintain, and cause significant operational constraints. Reliable collision and pedestrian detection is required.

Drilling

Semiautomated drilling of blast holes for the purpose of roadway/tunnel development or in open stope mining is now a reality. Drilling machines are available that can drill a ring of holes autonomously with little supervision over periods of a shift or more. There are strong control challenges with this class of machine due to the large outboard mass of the drill, the long telescoping arm which is compliant, combined with flexibility in the hydraulic actuators and the mobile base.

Drills are still manually placed and setup, and autonomous mobility and positioning would be the next development.

Explosive Placement

The loading of drilled holes with explosives, detonators, and primers is still an active area of robotics research [49.20]. Current practices see miners assembling detonators and primers and explosives are either pumped or placed manually into holes (with the aid of hydraulic machinery). Detonators and wiring are installed and linked back to an *exploder box* to initiate the blast (sometimes from a central location). This job is hazardous, not because of the handling of explosives, but because of the confined nature of the operation and the proximity of the miners to the hydraulic equipment (booms) and the solid tunnel walls. There are a number of robotics challenges associated with this task including locating the drill holes, assembling the primers and detonators, and inserting the hose into the drill hole. The positioning problem is hard for the same reason as for drill control: a large mass to be positioned using a nonrigid manipulator. End-effector-mounted sensors can be used to map the holes and provide the fine control to guide the explosive charging tube into the hole. Explosives and associated detonators can then be pumped into the holes as required.

Secondary Rock Breaking

One of the aims of underground hard rock mining to break the rock (most commonly with explosives) to a size that can be easily handled by the haulage vehicles, conveyors, and lifts. The spacing of blasting holes, their length, and the quantity of explosives used are optimized to achieve the ideal fragmentation size of the rock. However, sometimes a boulder is created that is too large to be handled. These rocks are typically broken with additional explosives in situ. Particularly problematic are large rocks that jam the flow of ore in the draw point of a block cave mine. Drilling and blasting these rocks is very hazardous and would be an a strong candidate for robotics.

There is a class of smaller boulders that can often be moved by an LHD or haul truck but that is too large to be fed into a rock crusher before lifting to the surface. The chute to a rock crusher is guarded by a grill called a *grizzly*. The size of the grill openings is made so that only rocks small enough to be crushed may pass through. Larger rocks do not fit and must therefore be broken

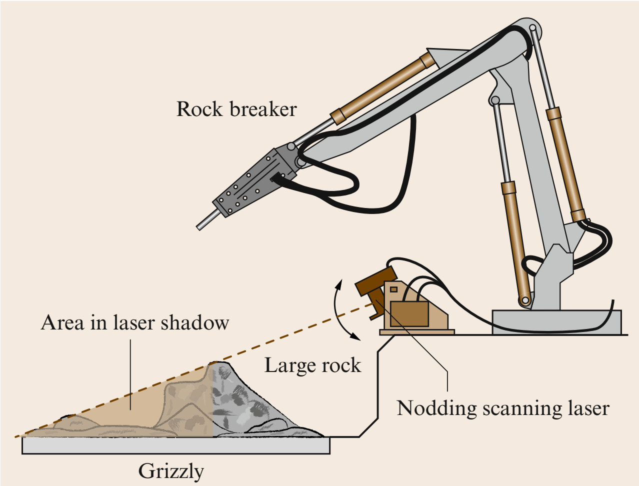

Fig. 49.11 Mechanical rock breaker

Fig. 49.10 Tamrock drill jumbo for developing tunnels in metalliferous mines

on the grizzly in order to pass through it. This job is carried out using a mechanical rock breaker, as shown schematically in Fig. 49.11. Rock breakers consist of a hydraulic or pneumatic jackhammer with a pick tool on the end mounted on a hydraulic multijointed arm driven by a human operator. The task of rock breaking is a logical one to be automated as, due to its infrequent nature, it is hard to justify a full-time operator when oversized rocks may occur a few times a day. The key research issues are sensing and perception, detecting when a rock needs to be broken, or simply needs nudging through the grizzly and then determining where on the rock to place the jackhammer pick in order to break the rock [49.21].

Metalliferous Roadway Development

Underground metalliferous mines use tunnels or roadways to access ore and facilities. These tunnels may sometimes be called declines, inclines, drifts, crosscuts, drives, and development headings depending on the function and region.

Traditional roadway development involves the steps shown in Fig. 49.12. Each cycle will extend the tunnel 3–6 m. The first step in the cycle is to survey and map the shape, location, and geology including grade and geological features. Note that the nature of the terrain has only been interpolated from drill core extracted at sparsely spaced locations. This work is done by surveyors and geologists before the ground has been supported. This is a hazardous zone which may not have settled since the previous blast. Research for robotic survey using photogrammetry, scanning lasers, and multispectral

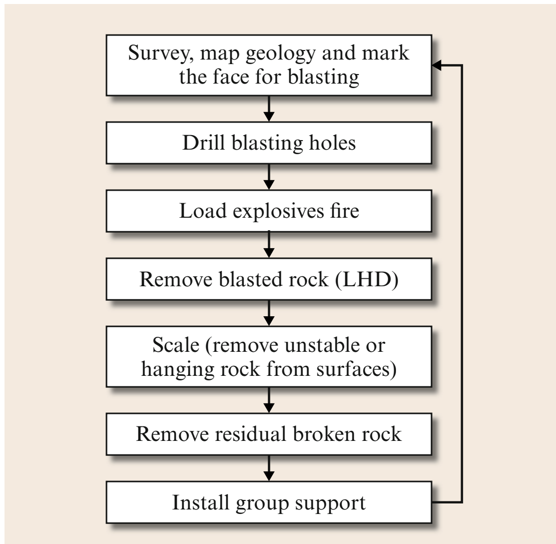

Fig. 49.12 Sequence of operations for tunnelling in metalliferous mines

analysis is in the early stages of development to acquire the necessary data without human entry.

Blast holes are drilled into the end of the drive in the direction of advance, typically using a drill jumbo (Fig. 49.10). Once blasted the rock is removed using an LHD to provide access for scaling. Scaling removes loose rock from the freshly blasted surface and this is done either by hand, or using a drill jumbo. More recently successful trials have been undertaken using high-pressure water-jet scaling. Scaling is a hazardous task that is worthy of robotic control.

Ground support may be any combination of one or more of: rock bolts, steel mesh (typically 2×4 m sheets), sprayed reinforced concrete (shotcrete) sprayed plastic resin. It serves to increase the stability of the tunnel walls and roof, making the area safe for humans to work in. Methods of installation range from manual to mechanized using purpose-built machines. No automated methods are known at the time of writing, but development projects are underway. Ground support installation is particularly suited to robotics since the working environment is dangerous.

In some roadways where the rock is relatively soft or long straight sections are required, tunneling machines similar to those used in civil tunneling can be used, but this is uncommon. Tunneling machines use rock cutters which make slow progress in hard rock. However, rock cutting has some significant advantages and with the development of improved cutting technology this may become a common method of roadway development in the future. Rock cutting can produce smooth surfaces that are shaped for maximum stress tolerance and do not require the same level of preparation such as scaling or the installation of ground support.

Geology-Based Guidance Systems

As people are removed from the active mining zones, they can no longer use their senses to assess local conditions. Hence the introduction of specialized instrumentation is necessary to provide feedback. The use of scanning lasers and inertial navigation instruments is now accepted and is used for geometrical navigation and condition sensing. A further step change in guidance technology can be realized through the development and application of sensors that are sensitive to geological features including marker bands and mineralization. The use of such sensors is being trialled in coal mining, as mentioned in Sect. 49.3. In metalliferous mining, there are no current applications but significant opportunity exists, for example, hyperspectral imaging adapted from satellite imaging can be used to identify and map the mineralization of a face to help guide a mining machine. *Fraser* et al. [49.22] have shown that hyperspectral radiation is sensitive to minerals of interest and this could be developed to allow a metalliferous mining machine to follow ore seams.

49.2.3 Case Study: Nonconventional Robotic Miner

A proposed new mining method being developed [49.8] will deliver a safer and more economic way to mine a range of ore body types. It is a radical departure from conventional mining, exemplifying a new mining method which can only be achieved with robotic technology. Known as ROES™ it has been developed to solve many of the current mining occupational health and safety hazards, reduce mining costs, and reduce the time to bring ore into production. These benefits will also allow some existing subeconomic resources to be mined economically, thereby increasing the stocks of available ore (*reserves*).

The system involves vertical or inclined access to ore bodies rather than traditional horizontal access and will use robotic equipment for all activities associated with drilling, blasting and survey. This reduces the amount and size of tunneling required (*development*) compared with traditional methods. The level of control and real-time feedback to mine operators will also deliver greater mining coordination and flexibility. Figure 49.13 shows a comparison between the geometries of the ROES™ and sublevel open stoping mining methods.

ROES™ involves three main robotic activities: drilling, explosive placement, and survey. All of the

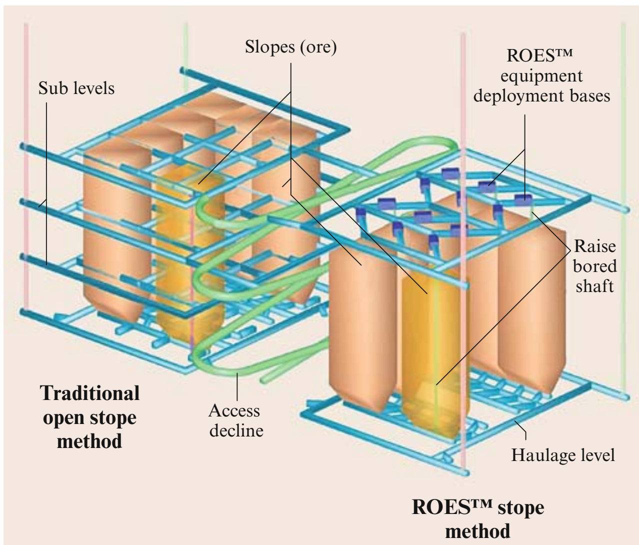

Fig. 49.13 Reduction in tunnelling required by ROES™ compared to traditional sub-level open stoping

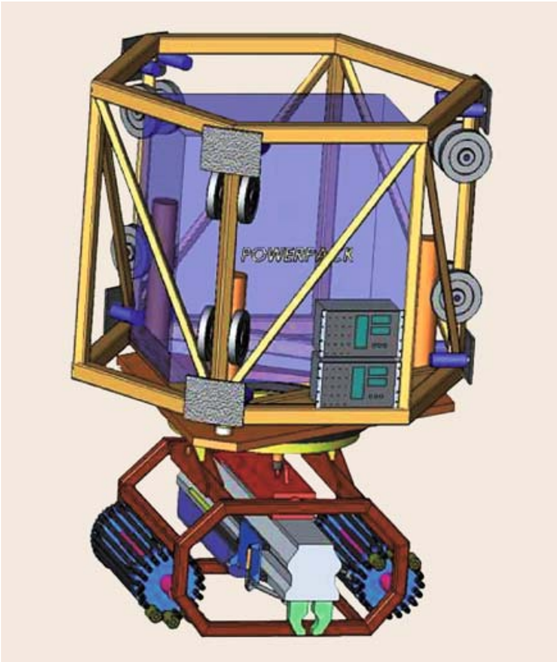

Fig. 49.14 Conceptual drilling module

equipment will be suspended from wire rope and deployed from the top of the vertical shaft to access the ore. The platforms will include onboard computers, PLCs, video cameras, machine encoders, and communications technology. Communication with the top of the shaft is possible via radio or infrastructure mounted into the support and power cables. Such methods exist and are in use in the mining industry.

The drilling machine (Fig. 49.14) will be relatively small and stiff, which improves the drilling accuracy which is very important, so the pose and location of the drilling machine must be known in relation to the ore body and other structures. During travel to the drilling zone, one or a combination of several methods can be used to track the pose and location: odometery from the winder, high-level onboard inertial sensor, and laser distance measurement from the top of the shaft. The use of reference laser, beacons or novel methods that observe and track the movement of the machine against the wall of the shaft are also possible.

The rock drill is mounted separately from the main platform to provide control over its bearing, vertical position, and pitch. Once in the approximate drilling location, the main support platform can be wedged tightly in place against the shaft walls using hydraulic rams. The fine position of the drill can be controlled by a combination of electric and/or hydraulic actuators. Drill rods and spare drill bits are mounted on conventional carousels mounted either side of the drill and a robotic arm is used to transfer them to and from the drill.

The explosive placement platform will be similar in concept to the drilling platform. A survey platform will also be used to determine the condition of the shaft, drilled holes, stope void and size distribution of the blasted rock in the void below using sensors such as: millimeter-wave radar, photogrammetry and scanning lasers.

49.3 Underground Coal Mining

While many aspects of the coal extraction process, either by continuous miner or longwall-based methods are now highly automated, there has been a generally low rate of adoption of robotics in the underground coal mining industry worldwide. Conventional automated industrial process control systems are universally applied to fixed infrastructure coal conveying and processing elements of the mining chain, but there has been little commercial adoption of techniques to autonomously or tele-remotely control the operation of the basic mobile and semimobile coal extraction equipment. Commercial systems are currently limited to simple line-of-sight radio remote control of continuous miners and longwall shearers. In this section we will explain why the adoption of robotics has been slow in this environment.

The immediate underground coal mining environment is a hazardous area due to the presence of potentially explosive atmospheres. Accordingly, regulating authorities impose strict rules to govern the design and implementation of electrical equipment. This in turn translates to the necessity for high investment to develop robotics technology for a relatively limited market.

The coal face area is a dynamic environment with a high level of both expected and unexpected changes in geological conditions. This requires continuous observation of the current mining conditions and rapid and appropriate response to these occurrences to sustain the mining process. This function is carried out by experienced human operators. It is a challenging task to develop appropriate sensing methods both for localization of the equipment and replacement of the human sensing ability to determine whether the equipment is mining coal or rock.

Despite these barriers, significant work has been done in developing robotics technology for this domain, particularly in navigation and sensing techniques and this section will explore significant issues, advances, and implementations.

49.3.1 Coal Mining Process

The nature of coal mining has led to the development of different styles of extraction equipment and potential robotics approaches. The longwall mining method, which accounts for the majority of underground worldwide production, is based on large equipment installations where motion of the individual components is highly repetitive and relatively constrained, whereas room (or bord) and pillar mining is more flexible, based on smaller mobile equipment.

Longwall Underground Coal Mining

In the longwall mining method ([49.23], Chap. 7) the primary extraction mechanism is a longwall shearer which has two ranging arms at the ends of which are rotating drums containing picks that remove the coal from the face. With reference to Fig. 49.15, the shearer travels along the face on a structure also housing an armored (or articulated) face conveyor (AFC) that carries the coal to one end of the face. The coal is then removed via other conveying systems to the surface. The roof is supported over this operation by a number of adjacent powered roof supports (also known as shields or chocks) which are each connected to the AFC. After the shearer passes, the chocks release from the roof, advance under hydraulic power into the cavity created by the removal of the coal, reposition the AFC and resupport the roof. The cycle then continues. Longwall face lengths range from 100 to 400 m and extraction rates can be of the order of 3000–4000 t/h. The advantages of the longwall method are the high sustained production rate and the ability to extract up to 80% of the coal seam.

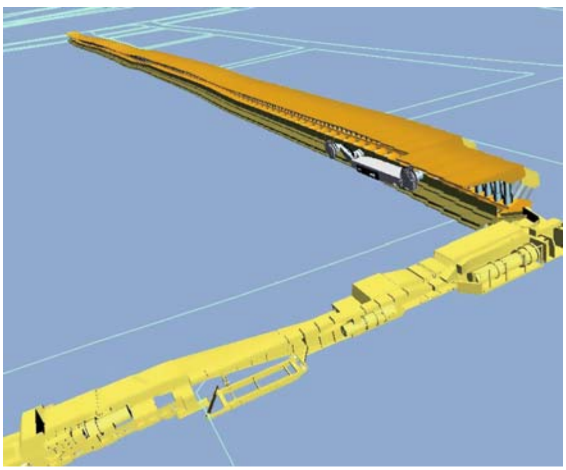

Fig. 49.15 Schematic of a longwall mining equipment installation

Automation has been applied to various elements of the longwall mining process, particularly face alignment and cutting horizon control. Significant work has been done in the development of sensors to detect the interface between coal and rock in order to automatically keep the extraction process within the coal seam [49.24–27]. Face equipment manufacturers have produced automation systems that currently allow remote control of both face alignment and cutting horizon of longwall operations. The motion of powered roof supports can be initiated by the passage of the shearer. The sequence of support motion and the distance each hydraulic actuator moves are also programmable. Consequently a desired profile of the longwall face in plan view can be generated and input to the supports.

Room and Pillar Coal Mining

The alternative common underground coal mining method is room (or bord) and pillar ([49.23], Chap. 6) where the extraction system is based on the so-called continuous miner (Fig. 49.16). This is a much more mobile item of equipment than the longwall and can utilize many aspects of vehicle robotics technology. The boom raises and lowers the cutting drum and the unit is driven and steered through the track drives. The tail of the continuous miner then delivers cut coal to a flexible

Fig. 49.16 Continuous miner

conveying system or to shuttle cars ([49.28], Chap. 9) that in turn link to fixed conveyor belt infrastructure. The method requires less investment to establish than longwall and can operate in a wider range of geological conditions but has a lower production rate and does not extract as high a percentage of the available coal. All mainstream continuous miners are now operated via radio remote control so in a logical extension, robotics applications to this method include teleoperation, navigation, and control of roof and floor extraction horizons.

Operational Constraints

The underground coal mining environment presents unusual impediments to the implementation of robotics technology. Perhaps the most significant of these is the existence of explosive risk zones due to the presence of methane and coal dust in the atmosphere where mining equipment operates. There are various protocols for the implementation of equipment that could trigger an explosion. At one extreme, equipment can be designed so that energy levels are low enough to make the equipment unable to release sufficient energy to ignite explosive gases and thus be intrinsically safe. This greatly restricts the functionality of such equipment and the development costs are very high.

The other major implementation method is to house commercial equipment in purpose-built protective *flameproof* enclosures which can prevent an explosion inside the enclosure from propagating into hazardous external atmospheres. While this enables flexibility in the equipment that can be used, there are rules governing the design and testing of the enclosures, so development processes are slow and costly. There are problems implementing sensing systems requiring provision of transparent or at least dielectric windows in the enclosures for visible light, infrared, laser or radar-based sensors, and even computer screens for user interfaces. The dimensions of such windows are restricted in order to be explosion resistant. Moreover, such enclosures must not be opened during operation so live testing of operational hardware is virtually impossible. On the up side, the necessity to provide such robust housing for electrical and electronic equipment has a benefit in that protection is also afforded against the usual problems of water and dust.

Highwall Coal Mining

The above underground mining scenarios are currently largely manned operations. Highwall mining is a derivative of room and pillar mining and can only be implemented by remote control. A series of parallel entries is made into the coal seam left exposed under the final highwall of a strip-mined open cut pit using a remotely controlled continuous miner. The coal is then conveyed to the surface by a continuous haulage method. In Fig. 49.17 continuous haulage is achieved using a series of interconnected conveyor cars. A *launch vehicle* is used to insert and remove cars, redirect the coal flow to a stockpile and as a location for an operator station. Supporting pillars of 1–3 m in width remain between adjacent entries, each of which can be up to 500 m long. If the entry spacing and pillar widths are not maintained then loss of equipment through roof falls and, in the extreme, catastrophic failure of a number of supporting pillars can result.

Fig. 49.17 A highwall mining operation

The rationale behind this method is that it is a low-cost way of extracting coal when overburden depths mean that open cut extraction methods are uneconomic. The method can extract about 60–70% of the available resource and then makes inaccessible deeper coal from other mining methods. Consequently the method is now falling from favor, being replaced by longwall operations with access roadways being driven directly into the seam from the highwall.

49.3.2 Scope for Robotics

Localization

Several of the methods described above require precise knowledge of the position of the cutting tool, and the underground environment is particularly challenging for accurate localization. To address this problem in the longwall context a shearer position measurement system (SPMS) based on inertial navigation has been developed [49.29] to accurately measure the three-dimensional position of the shearer.

Inertial navigation (INS) technology is a logical method to measure machine position in the mining environment. State-of-the-art ring laser or-fibre optic sensors are robust, often being designed for military applications. They require little or no connection to external sensors and thus can be located within the machine envelope in protected locations. The United States Bureau of Mines conducted tests using the Honeywell modular azimuth positioning system (MAPS) and subsequently the Honeywell ore recovery and tunneling aid (HORTA) units in the late 1980s for continuous miner guidance applications [49.30]. This work resulted in field trials in 1997 [49.31]. Further developments by CSIRO in Australia, resulted in the development of the first full-survey highwall mining guidance system in the mid-1990s [49.32, 33]. This system is now a critical requirement for highwall mining in Australia and is receiving increasing international acceptance.

The INS sensor is also applicable to longwall mining. If the real-time position and orientation of the shearer are continuously measured, the fact that the shearer passes over all the supports in a fixed geometrical relationship can be used to calculate the real-time positions of all the supports and thus the longwall face as a whole. This development, when added to existing manufacturers' capability, has facilitated reliable longwall face automation.

Planning and Control

Given better information about the position of the cutter and the position of the coal seam from geological models and online measurements it is possible to apply robotic path-planning techniques. However, true closed-loop control of face alignment has not been possible because there has been no reliable method to measure the true plan position of all the powered supports to provide accurate feedback to the control system. This process lends itself to the application of robotics in controlling the motion of the supports to manage face alignment and also the motion of the ranging arms on the shearer to position the extraction roof and floor horizons optimally in the seam.

Shuttle Cars

Currently the shuttle car operator docks the machine to the discharge conveyor of the continuous miner, controls the filling process, drives the shuttle car to a discharge point at a fixed conveyor, controls the emptying process, and returns to the miner to repeat the cycle. Often two shuttle cars are used in parallel to increase throughput so there are scheduling issues when one unit is required to wait for the other to unload or load. The entire operation could be automated using navigation developments already applied to LHD vehicles in metalliferous mining as described in Sect. 49.2.2. However no prototype or commercial shuttle car automation systems have yet been reported.

49.3.3 Rapid Roadway Development

Often longwall mining operations are delayed because the necessary gate roads have not been completed. Ground support in these roadways is often provided by roof and rib (wall) bolting. This is a relatively involved process in which firstly a hole is drilled into the strata using a portable or machine-mounted drill rig. The drill steel is then withdrawn and bladders of epoxy are manually inserted into the hole. Finally the bolt is inserted into the hole, again using the drill rig. The bolt is spun to break the bladders which mixes the epoxy and hardener to bond the bolt to the strata. Often the bolt is then tensioned to compress the strata to form structural support of the roof and rib.

Placement of bolts has been identified as a limiting factor in the speed of roadway development so there has been considerable industry attention given to improvement of the speed of bolting. Unfortunately the conventional bolting procedure poses several automation challenges shared also with other underground drilling applications discussed in this chapter. Automatic relocation of the hole in order to insert different devices to inject the epoxy grout and then to place the bolt is difficult to achieve in the operating environment. The development of a self-drilling bolt has eliminated several of the automation issues because it is now possible to drill a hole with the bolt itself and then leave the

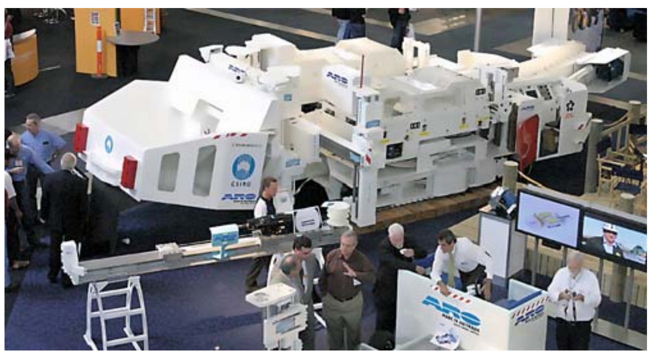

Fig. 49.18 Prototype machine for roof and rib bolting

bolt in place while the epoxy is introduced, mixed, and cured.

A system has been developed to implement automatic roof and rib bolting using a self-drilling bolt concept [49.34]. The major elements of this system, shown in Fig. 49.18, are removable cassette storage of bolts, an automated bolt delivery system, and automatic drilling/bolting rigs

49.4 Surface Coal Mining

Many different minerals are extracted in surface mining operations, for example coal (Fig. 49.3), oil shales, bauxite, iron ore, and phosphate. We can consider two different excavation requirements: removing the overburden which often covers the commodity of interest, and the commodity itself. The remainder of this section will discuss the general principles of excavation and material haulage using open-pit coal mining as an example. Most aspects of the process, and the types of equipment required, are common to many other open-pit mineral extraction operations.

A consequence of many years of commodity extraction is that all the remaining commodity is buried deeper than what has been removed to date. Miners refer to a stripping ratio, which is the ratio of the overburden volume that must be removed to access one tonne of mineral. Over the last 20 years, in the Australian coal industry for example, this ratio has climbed from 2–5:1 to 8–15:1 today. More material must be moved to reach the mineral, requiring a massive improvement in the productivity of overburden removal and a reduction in cost in order to maintain profitability – this is the challenge that automation and robotics can contribute to.

Various types of machine are commonly used for excavation. In approximately increasing size order: front-end (or wheel) loaders, back hoes, bulldozers, rope shovels, hydraulic excavators, draglines, and bucket wheel excavators. Front-end loaders, back hoes, and bulldozers are mobile plant that can be rapidly deployed as required. Their disadvantage is a relatively low productivity in dirt movement. Draglines and bucket wheel excavators have high capital costs, but operating cost per volume moved is very low.

From a robotic perspective, there has been important prior work in automating excavation machinery. *Singh* [49.28] provides a good treatment of much of this work using a number of implemented systems to illustrate the state of the art. Work at Carnegie Mellon University by *Singh*, Cannon, *Rowe*, *Stenz* and others in the 1990s, culminated in a comprehensive study and experimental evaluation of an autonomous 25 t hydraulic backhoe-type excavator [49.35]. This work included the development of techniques to estimate soil hardness and dig forces which were integrated into an autonomous digging control law, as well as methods for planning dig locations and clean-up operations. Other work in this area can be found in [49.36–40]. The smaller machines are typically hydraulically actuated and the control issues associated with such machines has been investigated by *Tafazoli* et al. [49.41] and *Bonchis* et al. [49.42,43]. Rope-shovels and hydraulic excavators are discussed in Sect. 49.4.2.

The remainder of this section will discuss the two main approaches to overburden removal for coal mining: the dragline excavator, and the truck-shovel operation in which a rope shovel or hydraulic excavator loads material into a truck.

49.4.1 Dragline Excavator

The dragline (Fig. 49.19) is the tool of choice for overburden stripping. Invented in 1904 for use digging the Chicago canal, the fundamental principles have changed little since, but they have evolved into truly massive electrically powered machines; see Fig. 49.3. Modern machines typically have boom lengths of over 100 m, weigh up to 5000 t, with bucket capacities of the order of 100 t.

They comprise a rotating assembly that includes the *house* (drive motors, controls, and operator cabin), tri-structure or mast, and boom. The house rotates on a bearing surface on top of the *tub* which sits on the ground. A large-diameter ring gear is fixed to the tub and the house is rotated by a number of pinions driven by motors in the house. While earlier and smaller draglines used a tracked base, the modern walking dragline drags its tub along the ground by means of large eccentrically driven *walking shoes* at the side of the machine. The dragline has three driven mechanical degrees of freedom: the house and boom rotate with respect to the tub; the bucket can be hoisted by a cable passing over sheaves at the tip of the boom; and the bucket can be dragged toward the house by a cable passing over sheaves at the base of the boom (Fig. 49.19). During digging, the

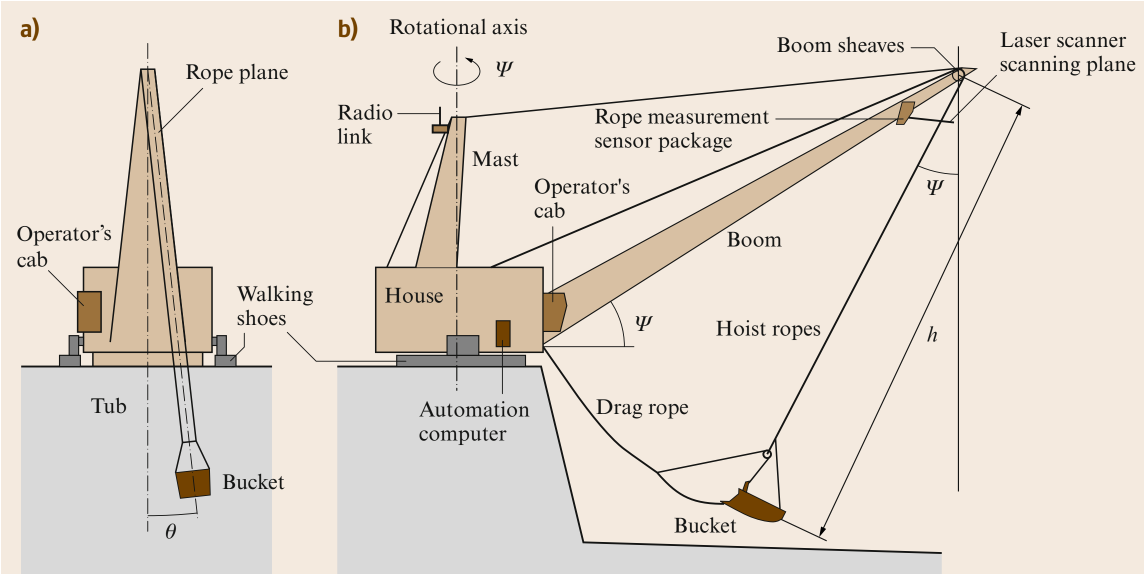

Fig. 49.19 Schematic of dragline

bucket motion is controlled using only the drag and hoist ropes. When the bucket is filled it is hoisted clear of the ground and swung to the dump position by slewing the house and boom. The drag and hoist drives now control the position of the bucket within a vertical plane that contains the centreline of the boom however the bucket is free to swing normal to that plane. Interestingly the bucket has three degrees of freedom within the boom plane but only two control inputs, making control of bucket orientation a complex function of position, speed, and rope tension [49.44].

Capital cost of these machines is of the order $US 40–80 M and the operating cost is approximately $US 5 M per year (labor, power, and maintenance) working 24/7. A dragline can only excavate to 50 m and with pit depths now well over 100 m the overburden must be removed in two dragline passes, or by using shovels and trucks (Sect. 49.4.2) to prestrip. The threshold depth at which underground mining methods would be employed continues to increase.

The issues facing owners of these machines are: maximizing productivity (m^3/shift) in the presence of operator variability and maintenance costs (around 30% of operating cost). It has been estimated that a 1% improvement in machine productivity is valued at around $US 1 M per machine per year. Operation is cyclic, and each cycle moves up to 100 t of overburden, and typically takes 60 s of which 80% of the time is swinging the bucket through free space. The work is repetitive, yet requires considerable skill. Performance can vary by up to 20% across the operator population, and for an individual will vary over a shift (up to 12 h).

The solutions currently pursued include: operator performance monitoring, improved training, and routine overloading of the machine which exploits the generous design safety margins and trades off productivity and maintenance costs.

Robotics offers the possibility of control that minimizes cycle time while bounding the stresses that cause machine damage. The challenges are to replace the human function of visually sensing the state of the bucket, its rigging and the local terrain and actuate the drag, hoist (joystick) and slew (pedal) controls in a coordinated fashion, controlling and exploiting the bucket's natural tendency to swing, while working within the significant voltage, current, and power constraints of the motors.

Early attempts at dragline automation [49.45] simply replayed the operator's control inputs but this failed because the control inputs are based on the instantaneous machine state which is a history of the initial condition and subsequent inputs, as well as the initial and goal states which vary from dig to dig. A key challenge is sensing the machine and bucket state which would include encoders on the motors and a noncontact sensor of bucket angles since the bucket is treated very roughly, being pulled through several meters of broken rock. Noncontact solutions involving computer vision [49.46]

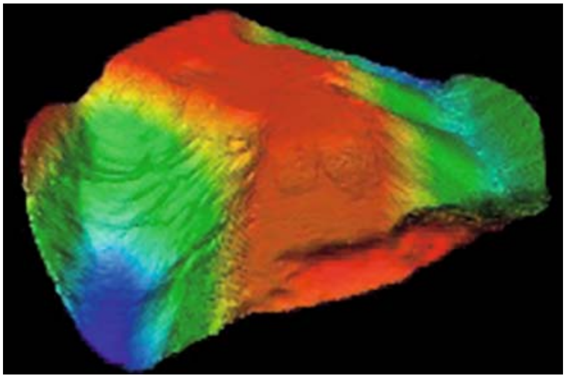

Fig. 49.20 Terrain mapping from the tip of a dragline boom

Fig. 49.21 A rope shovel dumping into a haul truck. A truck typically holds between one and three dipper loads of material (©CSIRO)

Fig. 49.22 A hydraulic excavator (©Automated Positioning System, Brisbane)

and laser range finders [49.47] have been proposed. Once equipped with sensors a dragline can be considered as a three-DOF (degree of freedom) robot (drag rope, hoist rope, slew angle) with a flexible, or unactuated, final link [49.48]. There are two control problems. Firstly the tool-tip (bucket) motion along a defined trajectory in free space [49.49] which is similar to that of controlling cable suspended loads for cranes [49.50], and consumes 80% of the cycle time. In a major production trial [49.51] a dragline automation system performing this free-space motion moved over 250 000 t of overburden in 3042 cycles over a 2 week period. Performance was equivalent to a human operator but the automation system had to lift the bucket higher in order to compensate for uncertainty in the environment. Mapping the surrounding terrain [49.52], as shown in Fig. 49.20, would allow the automation system to plan time-optimal collision-free paths.

The second control problem is moving the bucket through the ground in order to fill it, and determining when it is full. Some initial work in this area is reported in [49.53].

Another important consideration is a human interface that allows fast and seamless transfer between automatic and human-controlled operation [49.49].

49.4.2 Truck–Shovel Operation

As implied by the name the truck–shovel operation has two different machine types: a rope shovel (Fig. 49.21) or hydraulic excavator (Fig. 49.22) to excavate material and load it into the truck which hauls it away. While draglines have the lowest cost per unit volume removed (at least ten times more cost effective than a truck and shovel operation) they are very significant capital assets and difficult to move quickly around the mine. By contrast trucks and shovels can form more *flexible* operations since smaller individual units can be added or subtracted or readily deployed around the mine site.

Truck–shovel combinations can be used for overburden removal, either totally or in a prestripping mode in preparation for a dragline. Trucks and shovels are very commonly used to excavate the exposed coal seam.

The modern shovel (Fig. 49.21) is descended from the 19th century steam shovel and employs large electric drives and a cable transmission. Hydraulic excavators have a dipper mounted on the end of a rigid five-DOF hydraulic arm, typically on a tracked base. These machines are kinematically much closer to industrial robots, but on a massive scale, with dipper sizes over 20 m^3 available.

From an automation perspective [49.53] many of the issues are the same as for draglines: filling the bucket with broken rock, planning a time-optimal collision-free trajectory, and human interface. The rigidity of these machines simplifies the estimation of bucket tooth position.

Typically these machines swing and dump material into a haul truck, see Fig. 49.21. A perception system could be used to detect the truck and dump the material into a free area of the tray. Planning the motion of the trucks and the shovel becomes a problem in multirobot scheduling and path planning.

Blasting

The overburden is typically a soft sandstone, and the coal seam itself, after millions of years of compression, also resembles rock. In order to excavate it must first be blasted to fracture the material into pieces that can be excavated. A matrix of blast holes is drilled in the overburden layer and fired prior to overburden removal. The process is repeated with the exposed coal seam.

This process is amenable to automation, though it has not yet been demonstrated. The drill rig is a large-wheeled machine which needs to be positioned on the bench, and the drilling process itself needs to be automated. The drill string is assembled from short components as the drilling progresses. Online feedback from the drill head, speed, and torque, can provide geological data about the strata being drilled through. Accurate knowledge of the drill head is also required, since it can be deflected by geological conditions causing the blast to deviate from the design. Once the holes are all drilled there is scope for automating the explosive loading process: currently large tankers of explosive that visit each hole, insert a hose into the hole along with primers and detonators, and pump the explosive.

49.4.3 Surface Haulage

In surface mines, material (commodity or overburden) must be moved from where it is broken to where it will be processed or stockpiled. Haul trucks are the preferred means of moving material around a surface mine, typically diesel–electric vehicles with payloads of up to 400 t. The automation of these haul trucks has been an ongoing research and development activity for the truck manufacturers for over 10 years. Both Caterpillar and Komatsu (the two largest manufacturers of haul trucks) have had very active automation research programs. The key robotics challenges to the automation problem are localization and obstacle detection. GPS is an obvious choice as a primary localization sensor. However, GPS is not reliable close to the highwalls of a typical open pit (due to a lack of observable satellites and due to multipath issues). The ramps out of pits typically hug the walls, which makes the use of GPS as a localization sensor difficult. This problem can be solved using pseudo-lites to cover the GPS dead spots or other sensors such as laser scanner, radar, inertial guidance, and odometry in these areas. Both Caterpillar and Komatsu demonstrated autonomous driving of haul trucks in the late 1990s [49.54].

It is the area of obstacle detection that is far more challenging. Autonomous haul trucks must be capable of detecting rocks on the road in front that have fallen from other trucks. They may be required to detect other vehicles (if the haul road is open to other mine traffic) and they may be required to detect mine personnel. The development of robust obstacle detection systems for these vehicles is difficult because of the relatively harsh conditions encountered in mining environments. The operating environment could include rain, dust, mud, high humidity, diesel fumes (small particles), extremes of temperature, severe vibration, extreme vehicle pitching and rolling, and bright light sources (e.g., the sun). [49.55] shows how a 2-D scanning laser can be used to map the terrain ahead of a mining vehicle and hence be used to detect obstacles. Scanning lasers have been widely used for obstacle detection in the DARPA Grand Challenge [49.56] where nearly all competitors used such sensors as the primary means of detecting obstacles.

The technology for autonomous trucks has now been established but there are still very few examples of mines using autonomous haul trucks in regular production. It seems that the technology is ahead of the culture in this case and the mining industry is not quite ready for this big leap in autonomous operation. Instead examples of semiautomation or driver assists are starting to be tried. An example of this is the work in [49.57] where a collision warning system for haul truck drivers has been developed. This system uses many of the sensing systems of an autonomous truck but instead of directly controlling the truck the driver is alerted when he/she are starting to head off the road (maybe due to tiredness or inattention), or when another truck is on a potential collision course.

49.5 Conclusions and Further Reading

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 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.

Further reading on the state-of-the-art robotic mining machines in operating mines as at 2006 can be obtained from [49.1] and examples of current robotic miners include

- automated mobile haulage trucks in underground metal mines
- automated drilling machines [49.58, 59]

Areas of development, currently being researched, include

- a large and early challenge will be safe operation of mixed fleets, where robotic and manned vehicles operate in the same workspace,
- teleoperation, with immersive environments, is likely to grow in usage, but with the operators located thousands of kilometers away instead of actually at the mine site as is normal today. These telemining technologies will be essential when it comes to mining the rich but difficult to access mineral resources deep under the ocean [49.60] and on planets and asteroids,
- in situ processing of mineral ore by leaching to extract the metal, or in situ gasification of underground coal, remove the need to excavate and transport the material, much of which is waste. These methods will all require underground operations that are suited to robotics [49.61],
- microtunneling machines [49.62], or moles, will follow arbitrary paths through the groud, releasing gas from coal seams, or following narrow bands of commodity. Research in propulsion, localization, and communications will be required to make this a reality,
- automated explosive placement [49.20] and stoping methods [49.8],
- automated tunneling including installation of ground support [49.34],
- robotic rock cutting machines [49.63].

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