

Multimedia Contents



# Robotics in Mining

## 59. Robotics in Mining

Joshua A. Marshall, Adrian Bonchis, Eduardo Nebot, Steven Scheduling

This chapter presents an overview of the state of the art in mining robotics, from surface to underground applications, and beyond. Mining is the practice of extracting resources for utilitarian purposes. Today, the international business of mining is a heavily mechanized industry that exploits the use of large diesel and electric equipment. These machines must operate in harsh, dynamic, and uncertain environments such as, for example, in the high arctic, in extreme desert climates, and in deep underground tunnel networks where it can be very hot and humid. Applications of robotics in mining are broad and include robotic dozing, excavation, and haulage, robotic mapping and surveying, as well as robotic drilling and explosives handling. This chapter describes how many of these applications involve unique technical challenges for field roboticists. However, there are compelling reasons to advance the discipline of mining robotics, which include not only a desire on the part of miners to improve productivity, safety, and lower costs, but also out of a need to meet product demands by accessing orebodies situated in increasingly challenging conditions.

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There was a time, in recent history, when improved productivity and lower mining costs could be achieved purely by the economies of scale that arise from the use of larger equipment [59.1]. However, this era is likely over. Today's mining companies and equipment manufacturers have been making renewed efforts in the

pursuit of new and innovative approaches to the business of resource exploration and mining.

Among these efforts has been a move toward increasingly autonomous mobile equipment and processes. For example, major suppliers of mining equipment for both underground and surface mining operations now offer

robotic driving, dumping, and other materials handling functionalities. What is more, some global mining companies are now operating their own technology-focused divisions, each with goals of bringing new technological developments to their mines worldwide.

## 59.1 Modern Mining Practice

Mining is an ancient and broad practice, dating back to Palaeolithic times (43 000 years ago) [59.2] and involves the extraction of materials from the Earth's crust for utilitarian purposes. Today we mine minerals (e.g., gemstones, metals, salt, coal, and many others), aggregates, natural gas, and petroleum. These resources are used, for instance, to make the tools we use, shelter, food products, medicine, and clothing. Try to imagine, for a moment, a life where you endeavored to use (or build a robot from) absolutely nothing derived from mining. We benefit greatly from mining, but there is also increasing pressure and international recognition that the often negative environmental, safety, and social implications of mining and mineral processing must be curtailed and balanced with economic and lifestyle considerations. Robotics can play a vital role in all of these efforts.

In this section, we briefly provide some introductory background about the fundamental stages of mining, common to most operations, and discuss what drives the field of mining robotics, as well as its unique challenges, technical and otherwise.

### 59.1.1 Stages of Mining

Almost all mining operations have five fundamental stages [59.3]:

1. Prospecting
2. Exploration
3. Development
4. Exploitation
5. Reclamation.

*Prospecting* involves the initial search for valuable materials. This stage is normally carried out by geologists, and deposits may be located at or below the surface. Prospecting usually happens by either direct visual examination or by indirect methods (e.g., through the use of geophysical techniques) that look for anomalies in seismic, magnetic, electrical, electromagnetic, and/or radiometric variables of the Earth. Geochemistry and geobotany techniques are also employed. Although robotics has not yet played a pivotal

role in the search for minerals on the Earth, planetary geologists have been collaborating with roboticists for planetary prospecting; e.g., [59.4] and references therein.

Finally, there exist several emerging frontiers for mining, where robotics is already playing a critical role. These include not only very deep and high altitude mining, but also undersea mining and extra-terrestrial mining.

In the *exploration* phase, the objective is to determine as accurately as possible the size (*tonnage*) and value (*grade*) of a deposit. This process is sometimes called *delineation* and more often than not involves collecting samples of material by drilling. Similar to prospecting, robotic exploration drills for mining are not yet common for surface exploration on the Earth. However, there has been a significant amount of work on robotic drilling in extreme environments, such as undersea and planetary exploration; see [59.5] for a good introduction and ample references.

The development and exploitation phases of mining are where tools and techniques from robotics have been, to date, applied most. *Development* is the work necessary to bring a mine into production, and usual entails planning, design, construction (e.g., overburden removal, shaft sinking, underground access) and the installation of mine services (e.g., power, water, ventilation, etc.).

It is during the *exploitation* phase that the resource is physically extracted, processed, and shipped to buyers. How exploitation occurs depends on the selected *mining methods*, which depend on many factors. These include the spatial characteristics of the deposit, geologic conditions, geotechnical conditions, economic considerations, technological considerations (e.g., the availability of advanced tools), and environmental considerations. Generally speaking, mining methods can be divided into two categories:

1. Surface mining methods;
2. Underground mining methods.

Surface-mining methods are used when the deposit lies near the surface, are usually very large scale operations and have high production rates. Underground methods are used when the deposit is deeply buried. Such methods have lower production rates and are usually more technically challenging and hazardous for mine workers.

Figure 59.1 shows examples of robotic vehicles used in surface and underground mining. These technologies, among others, are discussed further in Sects. 59.2 and 59.3.

Mining must strive to meet the economic and environmental needs of the present while at the same time ensuring (or enhancing) the ability of future generations to meet their own needs. Mine *reclamation* is the process of closing a mine, recontouring, revegetating, and restoring the land and water to an acceptable post-activity state. The objective is to minimize any adverse effects on the environment or threat to human health and safety. Some reclamation activities involve the construction and monitoring of *tailings* impoundments, where waste from mining and resource processing activities is placed.

Recently, tools from robotics have been used to conduct bathymetric surveys of tailings ponds, which are unique environments with very specific safety requirements. Figure 59.2 shows a robotic maritime research vessel performing a bathymetric survey of a mine tailings pond at a potash mining operation in eastern Canada. Performing robotic surveys has been shown to be safer and more cost-effective [59.6].

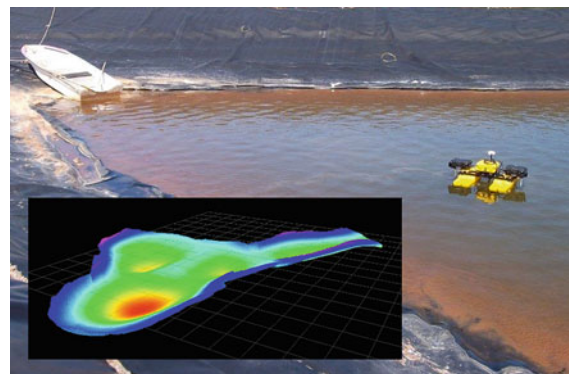


**Fig. 59.1** (a) Examples of robotic vehicles in underground and surface mining. Unmanned surface haul trucks (Photo: Mobular Mining Systems, 2011); (b) an autonomous underground load-haul-dump (LHD) machine at the Kvarntorp mine, Sweden (Photo: Joshua Marshall, 2007)

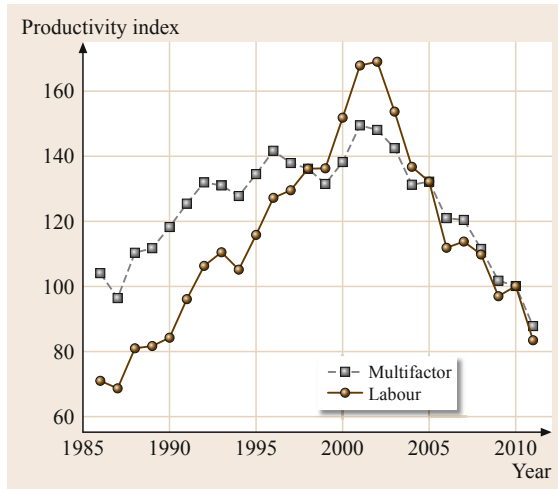
## 59.1.2 Technology Drivers in Mining

In order to better understand the potential for applications of robotics in mining, one must appreciate what drives the development of equipment technology in the mining industry. Mining is a dynamic process that must deal with the uncertainties of *outdoor* environments, and is usually conducted in as a series of interacting unit operations (e.g., drilling, blasting, loading, hauling, and processing). The harsh, extensive, and unstructured environments found in mining often preclude the application of existing techniques from other industries (e.g., from manufacturing robotics) [59.7, p. 806]. However, the recent growth of mobile and field robotics has resulted in several opportunities for robotics in mining. These opportunities stem mainly from a set of primary technology drivers:

- *Working Environment.* Mines are often developed in harsh and remote areas. For example, several companies operate mines and processing facilities at high altitudes. Also, as mines strive to operate at greater depths, extremely high ambient temperatures and humidity pose greater health risks [59.8]. Robotics may serve to minimize infrastructure needs and physically remove people from such hostile environments.
- *Labor Shortage.* Miners have reported difficulties finding the skilled labor needed to support their operations [59.9]. The newest generation of workers is technologically astute, but holds a different attitude toward physical labor than previous generations. Robotization may be what is needed to entice this new generation into mining.
- *Health and Safety.* With increasing mine depths, growing equipment sizes and speeds, and the tight-



**Fig. 59.2** Robotic maritime research vessel conducting a bathymetric survey of a mine tailings pond with overlaid example bathymetry map (Photos: Clearpath Robotics, 2013)



**Fig. 59.3** Experimental estimates of multifactor and labor productivity for the mining industry in Australia (1986–2011) showing decreasing productivity since 2001 (after [59.10])

ening of government regulations, it stands to reason that the deployment of almost any new technology that enhances the inherent safety of mining will be viewed positively at all levels.

- **Equipment Maintenance.** Maintenance costs and machine failures can make up a very significant portion of mine operating costs [59.11]. Moreover, operators often push equipment to its performance limits. Recent wisdom from the field of reliability engineering suggests that the automation (or

partial automation) of mobile equipment may help to significantly reduce downtime and maintenance costs [59.12].

- **Operational Efficiency.** There are a great number of areas in which efficiency improvements might be realized by the application robotics in mining. The most obvious lies in the fact that production time is lost during shift changes and breaks, resulting in much less than the desired 24/7 runtime. Not as obvious, and more difficult to quantify, is the less-than-optimal way in which underground mines typically operate. Without global and real-time control over the assignment (and movement) of machinery, the ability to optimize production performance through, for example, reduced dilution and increased recovery is also very difficult [59.1].
- **Sustainability.** Environmental and social responsibility are expected of modern mining companies and equipment suppliers. The alleviation of emissions (e.g., through the coordination and optimization of fleets) or reduction in power consumption by reduced operating demands (e.g., ventilation support) might be realized by way of real-time monitoring and automation of equipment.

Figure 59.3 shows multifactor and labor productivity for the mining industry in Australia between 1986 and 2011. Arguably encompassing all of the factors above, this data shows a worrisome decrease in productivity since the turn of the century, and some believe that robotics might help to reverse this trend [59.13].

## 59.2 Surface Mining

Surface mining is characterized by high tonnage operations, massive mobile equipment, and challenges that can include difficult environments (e.g., dust, fog, and extreme weather) together with remote locales and a strict need for keeping costs low.

### 59.2.1 Automated Haulage

*Haulage* is the process of moving material from one location to another. In the surface mining context, this is typically achieved using *haul trucks* (Fig. 59.1a), which move material from the point of blasting/excavation to the point of processing or stockpiling. The material being moved is either the desired economic quantity or overburden, and the destination is usually dependent on the load in the truck.

Haulage is a repetitive process, and the one to which automation can bring significant benefits, particularly


with respect to safety. Between 1989 and 1991, haul trucks were involved in 42% of the accidents and 60% of the fatalities in surface mining [59.14]. As with most mining equipment, there are also potential benefits of automation in the areas of productivity, repeatability, and reduced maintenance costs. Although it is too early in the history of robotic mining equipment to precisely define these benefits, the lessons from port automation (which use machines of similar scale, albeit in a more benign environment) have shown that maintenance costs of autonomous straddle carriers (in particular tyre wear and fuel costs) are reduced by approximately one-third [59.15] over their conventionally operated counterparts.

#### Autonomous Haul Trucks

Autonomous haul trucks can be thought of as mobile robots operating in a difficult, dynamic environment. As

such, they are required to have systems to address the standard issues of sensing and perception, situational awareness, localization, and control. The unique challenges presented in surface mining not present in other robotics applications include:

- Scale (haul trucks can carry up to 400 t of material).
- Mining pits often restrict the view of the sky, which can dramatically decrease global navigation satellite systems (GLS) reliability.
- Surface mining environments are constantly changing, which limits the ability to install fixed infrastructure.
- Mixed manually operated and automated fleets of machines, which places strict requirements on safety and integrity.
- All-weather operational requirements.

In the commercial sector, both Caterpillar and Komatsu had demonstrated the ability to automate haul trucks as early as the mid-1 990s [59.16]. However, it was not until 2008 that the first commercial deployment of Komatsu driverless trucks was realised in the Gaby Mine, operated by Codelco in Chile [59.17]. This was followed closely by a deployment by Rio Tinto at their West Angelas mine in the Pilbara, Western Australia [59.18] ( VIDEO 145), where they have operated continuously since and have moved more than 50 million t of waste.

The Komatsu trucks operate using a high-precision global positioning system (GPS) as the primary localization sensor, radar sensors for obstacle detection and situational awareness, a proprietary wireless communications system, and are given tasks (load, haul, dump, etc.) using a proprietary scheduling system developed by Modular Mining Systems [59.18].

At the time of writing, similar systems by Caterpillar [59.19] and Hitachi [59.20] are also in various stages of trial and deployment, although there is scant information available publicly regarding the specifics of their designs and operation.

The automation of mining haul trucks is still an area of active research, however, primarily due to the challenging nature of the mining environment as previously noted. New positioning systems [59.21], situational awareness systems (Sect. 59.2.10), and planning and scheduling algorithms [59.22] are all under active development, and are intended to improve robustness, safety, and productivity, respectively. If each of these challenges can be addressed, robotic haulage technology will be able to be applied in a much greater range of operational scenarios than is currently possible.

## 59.2.2 Fleet Management

*Fleet management* is a catch-all term that may define a number of different technologies used in mining. Commonly though, fleet management is divided into three main tasks:

1. Position (and perhaps materials) monitoring
2. Production monitoring
3. Equipment task assignment.

Fleet management solutions are typically deployed to an office environment and allow operators to quickly survey large amounts of mine data so that appropriate actions can be taken in real-time on the mine-site. Computerized fleet management must integrate and evolve with the deployment of robotic mining machines.

### Position Monitoring

The position of mobile equipment is commonly reported via wireless communications to a mine or region's database, where it can be queried by a visualization application. This provides a real-time picture of the movement of all equipment that has been enabled for such operation and allows an operator to quickly assess whether planned operations are proceeding as expected. Material movements may also be monitored in a similar fashion, but the material type (ore or waste) and grade must usually be entered manually by an operator. However some parameters, such as weight, are measured by the system.

### Production Monitoring

Given that vast quantities of data may exist (particularly from robotic machines) that give a historical account of the evolution of a mine, or group of mines, this data can be used to provide detailed reports to mine management, and may also be useful as part of a continual productivity improvement process. Examples of production monitoring data may include machine cycle times, average maintenance cycles, machine failure events, payloads, or combinations of parameters (e.g., machine failure events vs. machine payload weight).

### Equipment Task Assignment

At a typical mine, the equipment task assignment problem is addressed in a manner very similar to that of the urban taxi dispatch problem: A centralized authority decides, based on some predefined high-level goals, which machines must visit certain locations on the mine-site and perform some useful action. A machine

operator is generally given these instructions through a user interface located in the machine's cabin, which must be acknowledged and accepted prior to carrying out the task. The most typical implementation of the task assignment problem addresses the haulage scenario: when should a particular haul truck approach a given shovel, and when and where should it dump its subsequent load? Haulage is most commonly addressed, because it is here that even small changes in efficiency can have significant effects on overall profit.

### Commercial Solutions

There are many commercial solutions for fleet management in the surface mining. The dominant solution is Modular Mining's DISPATCH system [59.23], which was developed in the 1970s. It implements an optimization algorithm to allocate trucks to shovels and dump sites, and contains modules for the other tasks of production and positioning monitoring. Modular Mining joined the Komatsu group of companies in 1996 and helped to deploy the FrontRunner autonomous haulage system described previously [59.24].

Other commercial systems include Caterpillar's MineStar software [59.25], Wenco's fleet management solution [59.26], Leica Geosystems Jigsaw suite of software and hardware [59.27], and Devex's SmartMine system [59.28]. These systems all now offer very similar overall functionality and differ mainly in implementation details.

### Fleet Management Research

Although commercial systems for fleet management exist, there is still a substantial amount of research being undertaken, primarily in the area of task assignment optimization. Most commercial systems optimize task allocation using a heuristic that defines costs for allowing a shovel to become *idle* and/or allowing haul trucks to *wait* in a queue. In an ideal or optimal system, all items of equipment are fully utilized. However in practice, a higher cost is usually given to shovel idle time. The paper [59.29] gives a good overview of many of the commonly used heuristics used in task allocation optimization.

More recently, it has been acknowledged that heuristic, deterministic optimizers may not always produce truly optimal task assignments. This is primarily due to their inability to account for variability in the duty cycles of the items of equipment (i.e., they are stochastic rather than deterministic in nature), and any unforeseen discrete events, such as equipment failure, road blockage or operator error. The papers [59.22, 30–33] all describe recent approaches to overcoming these hurdles.

### 59.2.3 Robotic Digging

Mass excavation is one of the most important operations in mining. Being extremely sensitive to economies of scale and requiring a significant capital investment, it became a target application for robotic technologies starting in the mid-1990s. Surface mining typically uses large hydraulic excavators, hydraulic shovels, and electric rope shovels (Fig. 59.4). See also Sect. 59.3.3, which focuses on underground robotic loading.

Research in robotic digging involves systems design (including systems of systems), traditional robotics topics (sensing, planning, control), and tool-ground interaction problems. A framework for an intelligent earthwork system is suggested by [59.34], which discusses factors that can affect earthwork operation performance, identify key emerging technologies to support the implementation, the system architecture, and the system control strategy. A comprehensive review by [59.35] examined various aspects of sensing, planning, and control as they apply to earthmoving automation. Later developments in these topics are further discussed in [59.36]. Irrespective of the manned/unmanned aspect of the operation, a typical digging phase involves a number of critical steps: planning the bucket trajectory in contact with the ground, bank or muck pile; detecting when the bucket is full; and, detecting incipient stall and averting it. An analysis of autonomy requirements for each of these steps is detailed in [59.37] for the particular case of an electric rope shovel.

In other work, authors of [59.38, 39] proposed an autonomous excavation system for front-end-loader style machines that uses bucket force feedback, fuzzy logic, and neural networks for control. In their approach, a set of fundamental bucket action sequences,



**Fig. 59.4** A rope shovel dumping into a haul truck (courtesy of Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2006)

typically used by human operators, was compiled for use by the controller. A reactive approach, using fuzzy behaviours, was designed to act on force data to assess the excavation status and determine an appropriate control input. Experimental results, using a programmable universal machine for assembly (PUMA) 560 arm, were reported. Many more researchers have studied the robotic loading problem for homogeneous materials, such as soils and regolith. The majority of researchers have advocated the use of manipulator impedance or compliant motion control [59.40–43] and much of this work has focused on estimating the properties of the media [59.44] and on computing the resistive forces acting on the bucket during loading [59.45].

Invariably, all researchers agree that the biggest challenge to robotic excavation is the interaction between the tool and the terrain (ground, pile). This interaction is shaped by the properties of the media (e.g., density and hardness), the rock pile geometry, and the distribution of particle sizes and shapes. The problem is compounded by the fact that it is difficult to predetermine the exact nature of interactions prior to the execution of any particular excavation operation [59.46]. Significant effort was dedicated to modeling the interaction between the bucket and the terrain in excavation. This requires estimating the soil parameters online, since these parameters can vary significantly with the strata being excavated. The classical fundamental equation of earthmoving [59.47] used to determine the forces required for digging will fail to predict these forces if the soil parameters are not estimated correctly. Models for automated excavation using online estimation of soil parameters are discussed in [59.48].

Situational awareness, which includes both workspace and machine awareness, is another key aspect of robotic digging. Workspace awareness implies a knowledge of the terrain surrounding the digging machine. At a primary level, this knowledge is gathered using a sensor suite retrofitted to the machine, which in a typical configuration consists of a number of ranging sensors, an inertial measurement unit, and a GNSS unit. The acquired raw data is subsequently processed by higher level processes to detect the location and configuration of the dig and dump regions, and the location of other mobile equipment operating the workspace (e.g., haul trucks, utility vehicles). Laser rangefinders offer adequate resolution to segment the scene. An example of a workspace image in a form of a three-dimensional (3-D) point cloud acquired with a long range laser scanner installed on a shovel is shown in Figure 59.5. Color is assigned to the points based on intensity returns from the laser scanner.

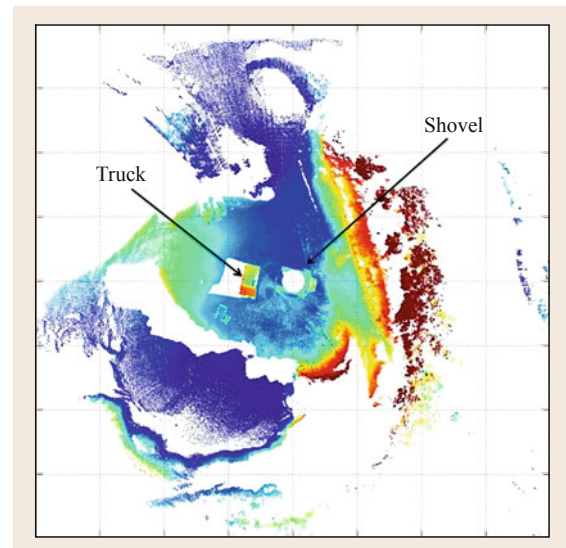
Machine self-awareness is primarily concerned with determining the position and orientation of the bucket

with respect to a referential fixed with respect to the machine. It also includes all the usual status data for the main onboard systems: power plant, transmission, tool actuation, etc.. The position and orientation of the bucket are usually available from encoders and inclinometers. A better solution, however, is to use suitably placed ranging sensors that are able to track the bucket in all positions and orientations [59.49]. This latter method avoids the errors typically associated with backlash in joints and dynamic effects in inclinometers. The placement of the ranging sensors on the machine should consider the need to provide an image of the ground under the boom.

Autonomous digging systems offer the additional benefit of enabling dig-to-plan operation and reconciling actual versus planned volumes by providing accurate real-time survey information. In surface mining operations, the floor is usually mined and therefore disturbed before accurate surveys are executed, and the floor is graded on an as-needed basis to facilitate the movement of the mobile equipment operating in the pit [59.49].

#### 59.2.4 Robotic Dozing

Dozers are used in most surface mines. Operating a dozer under conditions that are dynamic, with hazards that can vary and be subtle and difficult to recognize, adds to the complexity of the tasks that workers perform on these machines. Many of these tasks require oper-



**Fig. 59.5** A top view of a 3-D point cloud coloured by intensity returns from a long range laser scanner installed on a mining shovel loading a haul truck (courtesy of CSIRO, 2008)

ators that are highly skilled in ground-engaging tool control and machine positioning. In addition, dozer operators are exposed to a variety of risk factors that may lead to health problems, including whole-body vibrations, awkward postural requirements, noise, and shift work. While machine guidance systems are now ubiquitous, they still require an operator in the cab and have known problems associated with their reliance on GNSS-based localization. As alternatives, some equipment manufacturers offer tele-remote-controlled and autonomous dozers, which eliminate the need for an on-board operator.

Remote control solutions for dozers have been in use for two decades. They cannot perform in poor visibility conditions (dust, fog, night operation, heavy rain) and do not offer the possibility of automating machine guidance and tool control tasks otherwise available if operating the dozer from the cab. Other problems include loss of situational awareness, inaccurate attitude judgement, and inaccurate depth perception. More recent commercial remote control offerings include force feedback. In the case of tele-operated control with negligible latencies, imparting force feedback to the operator has the benefit of allowing the operator to *feel* and control the machine.

In view of the limitations of remote control technologies, research on dozer automation has focused on semi-autonomous and autonomous system retrofits. Autonomous systems have already made significant inroads in the mining industry, and the acceptance for this technology is growing. Leica Geosystems offers an autonomous ripping solution for track and wheel dozers. Their system, called Leica J<sup>3</sup> dozer autorip, provides a number of automatic functions, which include engine start/stop engine, automatic control for steering, throttle, transmission and ripper, accessories control, and an emergency fail-safe system [59.50]. The system also incorporates a path planner based on area coverage algorithms.

### 59.2.5 Autonomous Blasthole Drilling

Blasthole drilling is a mining process typically employed during the exploitation phase of surface mining. To excavate a material it must first be blasted to fracture the rock mass into small volumes suitable for haulage and processing. This is achieved by drilling a matrix of holes from the surface down into the rock mass; these holes are then loaded with explosives and blasted. The resultant fractured rock mass can be excavated by a variety of machines. The matrix of holes (or *drill pattern*) and the amount and type of explosives used are optimized to produce a desired rock size distribution in order to minimize the cost of processing; however, there

can be significant variation due to the variable nature of the underlying geology.

Blasthole drill rigs are usually large tracked vehicles with an articulated *mast* that contains the main drilling components: the drill motor, drill rods, and drill bit. To drill to depths longer than the mast, drill rods can be concatenated to form a long *drill string* as drilling is progressing. Like many home drills, most blasthole drill rigs are capable of rotary drilling, as well as hammer (or percussion) drilling. Rotary is typically preferred for softer materials, with hammer drilling primarily used for harder materials.

There are several facets of drilling amenable to automation: tramming (the process of moving the entire rig from one hole location to another), drilling, and the management of drill consumables (such as rod or bit changes). A *fully autonomous* drill rig should have all of these functions automated. The promise of automation is increased productivity and more consistency in the placement and angle of drill holes, which in turn should lead to better blasting outcomes. Consistency in post-blast fragmentation results in a significant economic impact.

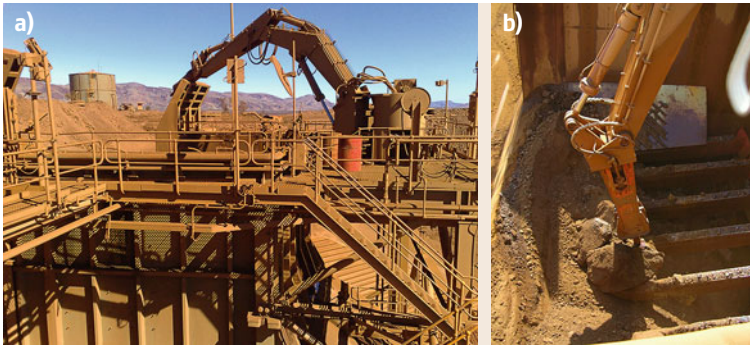
There are several high-profile mining equipment manufacturers and companies that have developed fully automated drill rigs. Atlas Copco's Rig Control System (RCS) has reportedly made significant impact in increasing average tramming speeds (from 0.8 m/min to 2.6 m/min) and drilling efficiency (a savings of 1 h per 12 holes drilled) [59.51]. Flanders [59.51], and Rio Tinto [59.52] also have fully automated blast hole drill rigs in production.

### 59.2.6 Telerobotic Rock Breaking

Drilling and blasting results are often far from ideal and the resulting fragments of rock (called *shot muck* or just *muck*) can be larger than the projected size. Some of the shot muck can be too big for handling with a digging machine, and thus requires a secondary blasting. Other boulders can be handled by the digging and hauling machines but are still too large to fit in the mouth of a primary crusher. In this latter case, rockbreakers are used to achieve a further reduction in ore and rock size.

A rockbreaker consists of a large 4-DOF (degree of freedom) serial link manipulator arm that is fitted with a hydraulic hammer (Fig. 59.6), and is usually positioned in front of a run-of-mine (ROM) bin. The bin is fitted with horizontal bars at the bottom that prevent oversized rocks from entering the crusher below (this arrangement is called a *grizzly*). The size of the grill openings is made in such a manner that only rocks small enough to be crushed may pass through. Larger rocks do not fit and therefore must be broken. Haul trucks car-





**Fig.59.6a,b** Rock breaker at rest over the ROM bin (a) and breaking a rock on grizzly (b) (courtesy of CSIRO, 2007)

rying ore from a nearby quarry dump their load into the ROM bin. Typically, an operator uses a line-of-sight remote control to operate the arm.

Rio Tinto is pursuing a programme to automate the vast majority of its Pilbara iron ore operations in Western Australia, and control the operations from the Remote Operations Centre (ROC) in Perth, situated over 1000 km away from the Pilbara region. This effort includes the development of a telerobotic control system for the primary rockbreaker at the West Angelas mine in collaboration with the CSIRO [59.53]. This system addresses known drawbacks in teleoperation (limited communication bandwidth, high latency in the real-time video feedback, lack of spatial situational awareness, etc.) by improving the intelligence of the control system at the remote/machine end (e.g., Cartesian motion and collision avoidance capability) and by providing the operator with a mixed-reality interface that combines live video with 3-D computer visualization.

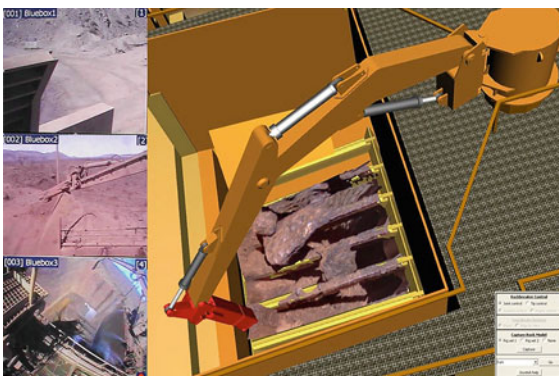
Each rockbreaker is fitted with a number of sensors to detect its pose in space, and actuated by signals that bypass the existing remote-control system. PTU (pan, tilt, zoom) cameras are fitted to poles on either side of the ROM bin and a pair of high-resolution digital

stereo video cameras were mounted below. At the remote end, in the control room, the operator is presented with an overview of the rockbreaker from a wide-angle video stream augmented by a synthetic computer image (Fig. 59.7). The operator is able to *walk around* the rockbreaker in the virtual world and inspect the rocks from different angles, enabling the operator to determine the appropriate breaking strategy. The operator deploys the arm using commands from a joystick, and as the arm is commanded to move, the motion of the arm is replicated in the 3-D scene. Simultaneously, both PTZ cameras follow the tip of the hammer. When the operator is ready to break the rock, he/she can switch his/her attention to the live video stream, which can be used to monitor the breaking of the rock. Once complete, the arm can be automatically sent to the rest position.

### 59.2.7 Automated Loading Unit and Truck Interactions

The main loading units used in surface mining are electric and hydraulic shovels and hydraulic excavators. Given the large volumes of material that need to be moved, and the comparatively small size of loading and hauling units, cycle times are closely monitored. In the continuous pursuit of efficiency, mining engineers dissect cycles to look for potential savings. One area of interest is truck spotting, which is the process of manoeuvring the haul truck into a position and orientation that is ideal for the loading unit to dump material into the truck's tray (Fig. 59.4).

The ideal truck placement for loading has both productivity and safety implications. When a mining shovel is used for loading, the haul truck must be positioned in such a manner that the swing motion of the shovel is minimized and that the shovel boom does not need to lower excessively to reach the tray. If the haul truck is not placed optimally, the loader needs to reposition itself to tip with a full load in the bucket, which results in lost time. Lowering the loader arm excessively and/or an uneven distribution of load in the haul truck



**Fig. 59.7** A mixed reality user interface combines live video and 3-D stereo reconstruction of the rocks above the grizzly (courtesy of CSIRO, 2008)

tray may result in injuries to the operators and property damage.

In open-pit mining, the shovel operator usually guides the haul trucks to the desired location (spotting) by placing the bucket in the location that is optimal for the dumping phase, and waits for the truck to move into position. A key requirement for achieving automatic spotting is the availability of a robust localizer, that determines the relative pose between the shovel and the truck. Currently, most of the commercial guidance solutions are based on the use of GNSS and GNSS-aided inertial navigation systems on both the shovel and the truck. This results in an indirect determination of the relative pose between the shovel and the truck.

These systems, however, do not provide a robust solution. For the haul truck, the proximity to the shovel boom and crowd arm can lead to a degradation of the GNSS solution due to multipath, while the placement of the truck near highwalls leads to a partial obstruction of the sky, with a loss of satellite tracking and a significant geometric dilution of precision. The guidance system on the shovel can be impacted detrimentally by the proximity to highwalls. Imaging sensors (e.g., laser scanners) can be installed on both the shovel for a direct determination of the relative pose between the shovel and the truck [59.55]. However, this solution has potential pitfalls, that are related to the sensitivity of the imaging sensors to environmental conditions such as dust, rain, and variable illumination during the day (or during the 24 hour day/night cycle in cases where cameras are used).

Some researchers have looked at modalities that mitigate these pitfalls. One possible solution, suggested

in [59.54], is to divide the space around the shovel into three zones: the outer zone, the handover zone, and the work zone (Fig. 59.8).

The relative size of the zones depends on the truck and shovel geometries, and the chosen safe operating speed limits within each zone. As the truck crosses into the handover zone from the outer zone, the spotting system flags the truck as active and begins sending commands to it. In this zone, the relative pose between the shovel and truck is determined indirectly, based on the method discussed above. In the handover zone the truck is sufficiently far from the shovel and the highwall, and therefore the localization errors due to multipath and sky occlusion are minimized. Once the vehicle crosses into the work zone, the spotting system begins computing the relative pose using the imaging sensors on the shovel.

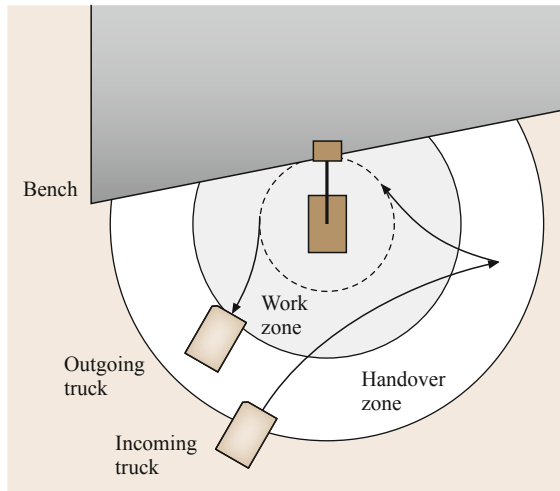
Since the sensors on the shovel are also able to see the bench and other obstacles in the work zone, the shovel is able to direct the truck around obstacles as they appear in the work zone, and park the trucks as close to the bench as practical. In other words, since the shovel is actively aware of its environment, it is able to deal with changes to the environment as they occur. The spotting system generates an approach path that will bring the truck in the optimum position for loading, where this optimum is determined in relation to the characteristics of the shovel and the configuration of the dig face. The path is also optimized with respect to the positioning time. Spotting times may be further minimized by double spotting, when the shovel loads on both sides, as depicted in Fig. 59.8.

The above discussion focused on shovel–truck interactions. Similar issues arise when hydraulic excavators are used for loading. Comprehensive research results in autonomous truck loading using hydraulic excavators are discussed in [59.56].

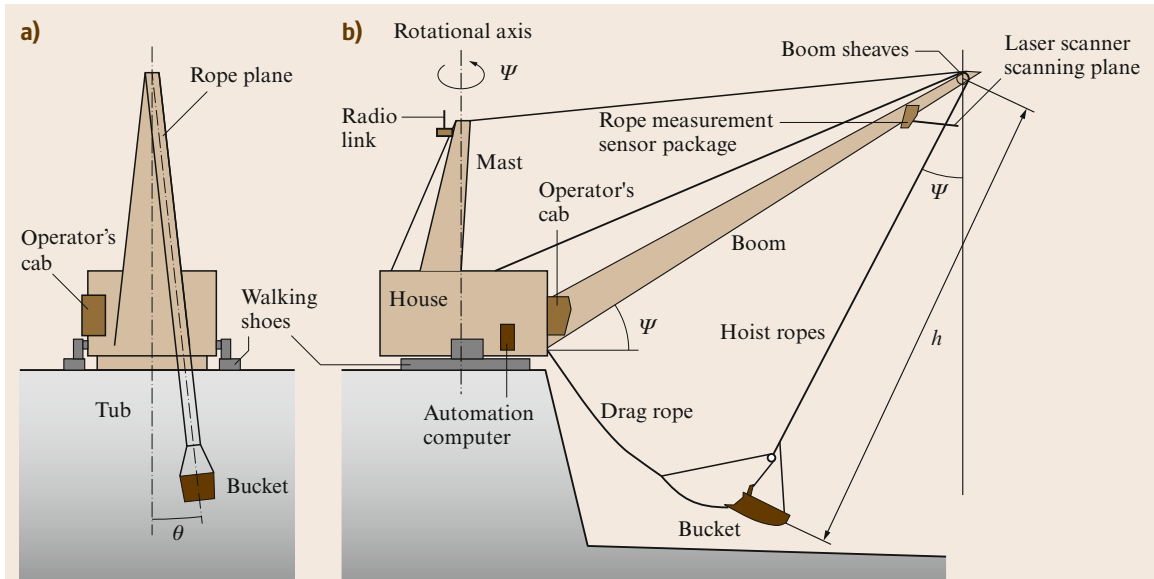
### 59.2.8 Dragline Automation

Mining *dragline* excavators are massive electrically powered machines used in open-pit coal mining to remove overburden and uncover coal. A dragline comprises a rotating platform that supports the house (consisting of the engine room and operator cabin), boom and a bucket rigging structure, as illustrated in Fig. 59.9. The house rotates on a base known as the tub which rests on the ground. The mechanism has three degrees of freedom:

1. Rotation with respect to the tub;
2. Hoist by a cable passing over sheaves at the tip of the boom;



**Fig. 59.8** Traffic management zones around a shovel in a double-spotting configuration, when the shovel loads on both sides (after [59.54])



**Fig.59.9a,b** Schematic of a dragline excavator (a) front view (b) side view (after [59.2])

3. Drag by a cable passing over sheaves at the base of the boom.

Digging 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 swinging the house and boom. The human operator fills the bucket by dragging it through the ground, lifts and swings it to the spoil pile, dumps it, and then returns to the dig point. Each cycle moves up to 100 t of overburden, and typically takes 60 s.

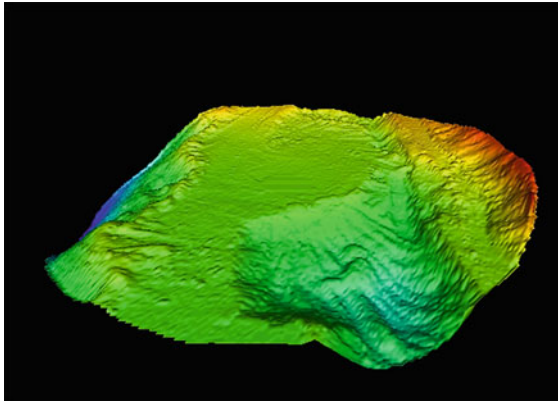
High capital costs are pushing the owners of these machines to continually look for avenues to maximize productivity ( $\text{m}^3/\text{shift}$ ) in the presence of operator variability and maintenance costs (around 30% of operating cost) [59.2]. From this perspective, dragline operations seem ripe for deploying robotic technologies. However, the idea of completely removing the human operator from the dragline seat, while tempting from a research perspective, it is not widely entertained in the industry.

Swing control and digital terrain mapping are the two robotic technologies at the core of the dragline automation efforts. During dragline operation, the bucket naturally tends to swing with respect to the boom. A skilled operator can coordinate the boom slew motion so as to control the natural tendency of the bucket to swing during dumping and spotting operations. A novice operator typically requires six months training to become proficient. This warrants the development of a swing automation system to improve the productivity of the dig-to-dump and dump-to-dig phases of

a dragline operation. Automatic swing controllers offer the additional benefit of minimizing stress fatigue on the boom.

An implementation of a dragline swing controller is discussed in [59.57]. The control system moves the bucket between operator-specified dig, and dump points, passing through intermediate (via) points. The rather rigid programming of control (dig, via, and dump) points has a number of disadvantages. Firstly, as the spoil pile grows the dump point must be raised. If the automation system does not contain a model of spoil growth, the operator has to make adjustments by re-training the system, resulting in time losses. Secondly, if the operator does not correctly identify a via point at a critical area, such as the top of the high wall, the swing automation system will not know the high-wall is there and may attempt to swing the bucket through it. Augmenting the automation system with a digital terrain mapping capability provides a common solution to these problems.

One implementation of a digital terrain mapping solution for draglines is described in [59.58]. Maps were created using data from a real-time kinematic (RTK) GNSS system and a two-dimensional (2-D) laser scanner. The laser scanner was mounted at boom tip in such a way that the scanning plane intersected the ground underneath the boom, and tilted by about  $7^\circ$  with respect to the vertical. Tilting the laser minimizes the likelihood of the bucket and ropes blocking the laser's view. The terrain is scanned as the dragline swings during the normal operation cycle, a typical map is shown in Fig. 59.10.



**Fig. 59.10** Image of a digital terrain map created from a long range laser scanner installed at the tip of a boom dragline (courtesy of CSIRO, 2005)

The implementation of a digital terrain mapping function in dragline automation systems also enables the measurement of dragline productivity in real time. Commercial dragline monitoring systems can only measure the approximate weight of each bucket, and the approximate disengage and dump points. They cannot provide indications of where the where the spoil is located in relation to the dragline, of the actual volume of overburden moved, or how much re-handle took place [59.58].

### 59.2.9 Machine Positioning and Terrain Mapping

The task of establishing and maintaining the vehicle positioning (i. e., position and orientation) relative to an external frame of reference is a fundamental problem in autonomous vehicle navigation and control, and this hold true for mining applications. High-accuracy positioning technology is a dynamic area of research and development, spurred on by the advances in satellite positioning as well as by the current challenges for the technology in mining systems, especially in surface mining operations. The following initiatives are underway to improve the availability and robustness of current technologies, which have and will further enable the application of robotics in surface mining:

- Public GNSS systems (e.g., GPS and GLS (global navigation satellite system))
- Augmented public GNSS systems (e.g., GPS with WAAS (wide area augmentation system))
- Locally augmented GNSS systems (e.g., DGPS (differential global positioning system) or RTK GPS)

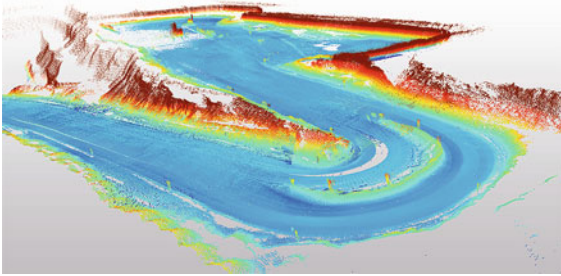
- Pseudolite augmented GNSS systems (i. e., through the installation of Earth-based transceivers)
- Closed systems (i. e., wholly proprietary systems relying on a constellation of locally installed Earth-based pseudolites).

For example, in the mining domain, Leica Geosystems offers the Jigsaw Positioning System (JPS), a product that offers a significant breakthrough in addressing the major shortcomings of GNSS [59.59]. Based on a technology developed by the Locata Corporation [59.60], JPS is a ground-based network for positioning that in principle mirrors the functionality of GNSS. It circumvents the fallacies of GNSS by using a terrestrial network of transmitters that can be placed in optimal locations with respect to the mobiles being tracked.

Different from pseudolites, an example of technology for positioning in GNSS-denied environments is CSIRO's wireless ad-hoc system for positioning (WASP) wireless tracking technology. The system can be configured as a mesh network and offers a unique combination of high accuracy, high resistance to multipath interference, low-cost hardware, and ability to be rapidly deployed [59.61]. The accuracy of WASP depends upon the radio propagation environment, and is typically better than 0.25 m under line-of-sight conditions, even in the presence of substantial multipath interference. The maximum range over which WASP nodes can measure range and communicate is typically over 400 m, and can exceed 1 km. As WASP can form a mesh network, the overall network size is not limited. The maximum location update rate is 200 Hz; however, there is a tradeoff between the number of nodes and update rate, and a typical update rate is 1–10 Hz.

#### Terrain Mapping and Surveying

The penetration of robotic and autonomous systems in mining, coupled with new computer aided tools for mine modeling and reconciliation, requires more accurate and timely information about the current state of the mine, and at higher spatial and temporal resolutions. In the traditional surveying framework, one obvious solution is to increase the number of surveys (reduce the time gap between successive surveys) and the density of survey points, while reducing the costs per survey. To address this, a number of vehicle-based scanning systems have been recently introduced to the market. The mode of operation ranges from stop-and-go-type systems (such as the Maptex I-Site), to continuous scanning mobile systems, such as those offered by Riegl (VMX 250), Topcon (IP-S2), and Trimble (MX-8). In general, these systems integrate high-end LIDAR (light detection and ranging) with GNSS-aided INS (inertial



**Fig. 59.11** A 3-D map of a surface mine created from a mobile mapping system installed on a four wheel drive (4WD) vehicle (courtesy of CSIRO, 2012)

navigation system) and carry a significant price tag, which can limit deployment to a single dedicated survey vehicle.

On the other hand, consider the application of simultaneous localization and mapping (SLAM) in mining. SLAM is a mature area in mobile robotics and efforts are underway to transfer the technology to mining. Data-fusion techniques used in SLAM make it possible to use lower cost mapping sensors, which in turn enables mining companies to deploy the equipment on a multitude of utility vehicles and/or heavy-duty mining equipment (Fig. 59.11). As a result, the vast majority of survey work can be performed during the normal operation of the equipment in pits, on haul roads, or other site areas, without directly exposing surveying personnel to the perils of conducting survey work in high-risk areas.

### 59.2.10 Mine Safety

The increase in demand for resources has posed new challenges to increase productivity, while at the same



**Fig. 59.12** Complexity of mining equipment interactions affected by adverse environmental conditions (courtesy of CSIRO, 2012)

time continually improving the standard of safety. Robotics is beginning to play a role in this. There are inherent risks associated with manually operating vehicles in mining environments. Operators work long shifts and the view from the driver's cabin can be very restricted. Furthermore, vehicle interactions are inherently difficult due to the size of machines, and can be further complicated by environmental conditions such as dust, fog, and snow (Fig. 59.12).

Each year there are hundreds of mine haulage accidents that result in significant numbers of injuries, even deaths, and large financial costs due to machine downtime and repair of equipment. According to the United States Mine Safety and Health Administration (MSHA) [59.62], from 2002 to 2008 the United States coal industry alone averaged 1206 accidents per year involving mobile equipment.

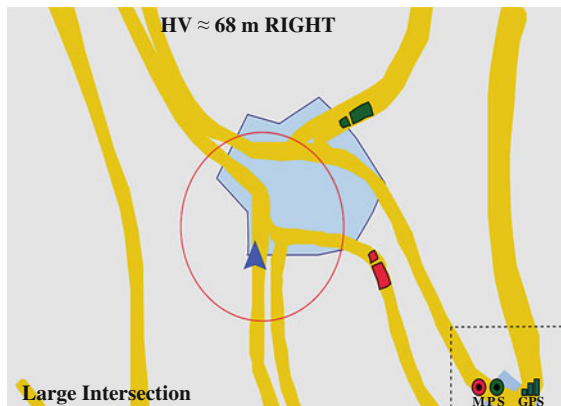
During the past few years, a number of approaches have been introduced to assist operators in becoming more aware of safety risks in the local environment. These technologies and methods include proximity awareness technology (PAT), proximity detection technology (PDT) and collision avoidance technology (CAT). It is important to note that, in surface mining, these existing technologies do not perform any control action. They merely provide information to the driver, who remains in total control of the vehicle.

#### Detection of Threats

In general, most safety incidents are from vehicle interactions with other vehicles, fixed infrastructure, or personnel. A large proportion of these incidents happen at low speed. This is most likely to occur on vehicle startup, or at the loading areas with interactions between trucks, shovels, loaders, and other ancillary equipment. These accidents are usually of low impact but can cause serious damage to equipment and significant loss of production.

The fundamental approach to reducing the likelihood of low-speed incidents is to provide the operator of large vehicles with aids to see into blind areas such as side or back of the vehicle. These aids are normally based on standard video or infrared cameras. The next level of risk reduction is achieved by incorporating automatic detection of resources and people in close proximity by utilizing range and bearing sensors. Radar is a preferred sensor modality for bad environmental conditions. Wide beam radars are very common but they are prone to false alarm. New recent developments mitigate this problem by using electronic-mechanical scanning narrow beam radar technology [59.63, 64].

High-speed incidents occur less frequently than at low speed, but often result in serious injuries and fatal-



**Fig. 59.13** Graphical representation of the state of the world close to the vehicle, including other vehicles in proximity, maximum risk, most likely paths, and risk areas (context) (courtesy of Eduardo Nebot, 2011)

ities. The time available to stop the vehicle or perform an evasive maneuver is reduced and consequently long-range detection of threats is necessary in order to take early preventive action.

This is addressed by incorporating vehicle-to-vehicle (V2V) communication with all nearby vehicles at sufficient range to provide early warning of potential threats. V2V networks can also form a mesh structure. The fundamental advantage of this approach is that no fixed infrastructure is required, and communication between vehicles can be guaranteed anywhere in the site when vehicles are in radio range.

#### Positioning, Context, and Road Maps

Positioning is one of the fundamental components of a comprehensive safety system. The incorporation of

GNSS systems, integrated with velocity and inertial observations, allows for the evaluation of reliable time-to-collision (TTC), especially when combined with haulage road maps information.

Determining the risk of a situation is entirely dependent on the context of the situation. One important situation context is the location, or more specifically the type of area the vehicle is currently operating. The expected behavior and driver intent [59.65, 66] varies depending on whether they are driving on a road, parking in a designated area, or dumping ore in a crusher. Map information is required to allow the system to vary the information provided to the operator depending on the location. An example is shown in Fig. 59.13, where the map allows the operator to become aware of the risks, and complexity of the situation, independent of the weather or geometry of the terrain.

#### Monitoring and Design

The ultimate goal of any safety system is to find a complete solution to the safety problem by introducing new technology, methods, and algorithms. It is very unlikely that this can be achieved with a single technology alone, perhaps with the exception of a fully autonomous system implementation. An active area of research and development aims to use both reactive and proactive approaches to solve the safety problem. At the reactive level, technology is used to assist the operator in recognizing and avoiding the safety risks. At the proactive level, managers are provided with tools to monitor, analyze, design, and improve the safety of the mining operation. This new comprehensive approach to safety has the potential to eliminate all accidents in the mine by integrating technology, procedures and intelligent algorithms to make the mine safer and more productive.

## 59.3 Underground Mining

The especially hazardous and generally unpleasant nature of underground mining environments, operator safety and fatigue, labor costs, and the repetitive nature of the ubiquitous load-haul-dump cycle all motivate autonomous and semi-autonomous and teleoperation-based solutions for underground machines and processes.

### 59.3.1 Telerobotic Operations

In mining, *remote control* typically refers to the control of a machine where the operator has a direct line-of-sight view of the machine. Remote control is normally used only for excavation (or *mucking*), not for driving

(or *tramping*) of loaders, for instance. Remote control systems are widely used, for example, when loaders must access underground drawpoints where there is a risk of falling ground.

By remotely operating equipment or through the partially autonomous operation of equipment, for example, it stands to reason that the exposure of personnel to unsafe circumstances might be significantly reduced. This was argued to be true at Inco Ltd. during the 1990s [59.67].

*Telerobotic* systems are those in which a human remains part of the control loop, although *at a distance* and not generally within direct view of the system being controlled. Many mining companies and equipment

manufacturers are now finding benefit in the application of telerobotics, particularly to underground equipment such as LHD machines (Fig. 59.1b) and drills [59.67–69]. This is normally done by the real-time transmission of video and control signals to and from a remote control room; Figure 59.14, which shows a commercial teleoperation station.

However, teleoperated equipment may not be as productive as manually operated equipment, for example, due to visibility and issues related to reduced operator feedback. Recently, some researchers have proposed the development of semi-autonomous teleoperation systems, whereby the operator's actions are filtered by a machine control system that regulates operator commands with some degree of partial or *local autonomy* [59.70].

### 59.3.2 Autonomous Trammig

Autonomous *trammig* refers to automating the driving task of underground mining vehicles, which is often a repetitive activity. Most robotic trammig systems have been developed for LHD machines, such as the one shown in Fig. 59.1b, although some suppliers also have systems available for their underground haul trucks.

Several challenges exist that make the autonomous trammig problem difficult. For example, the large inertia of these vehicles and their hydraulically actuated, center-articulated steering mechanisms make them difficult to control at high speeds. Another is the problem of precise and real-time underground localization in the absence of global infrastructure (most notably, GNSS available on the surface).

#### Underground Navigation

Early autonomous trammig systems worked by outfitting the mine with signal-emitting cables [59.71],



**Fig. 59.14** Teleoperator's station for control of underground robotic vehicles at the Kemi mine, Finland (courtesy of Atlas Copco, 2009)

reflective strips [59.72], light-emitting ropes [59.73], or reflective tape [59.74, 75]. Other systems required beacons, placed at strategic locations throughout the mine, which allowed the vehicle to estimate its position by measuring angles to the beacons and comparing the measured angles to those expected from a map of known beacon locations [59.76].

One drawback to these early systems is the time-consuming task of installing, localizing, and maintaining the necessary infrastructure, particularly as the mine advances. To the best of our knowledge, none of these systems ever saw widespread use in industry. The state of the art in underground autonomous vehicle systems is infrastructureless.

One of the first infrastructureless technologies was one initially developed by an Inco Ltd. spin off. The patent [59.77] describes the use of a map consisting of a set of interlinking nodes intended to represent the topology of the underground passageway environment. The nodes themselves are located at points of interest, such as at intersections, dead ends, etc. Thus, a topological map was used for navigation, which relied on an algorithm capable of classifying all of the possible tunnel geometries encountered in the mine. Steering the vehicle was then done by a lower-level reactive algorithm, which tried to keep the machine near the tunnel center. A range-sensing device was used to sense the distance to walls.

This topological and reactive approach to underground navigation and control was tried again after [59.77]; see also [59.78–81]. Recently, these methods have also been combined with radio frequency identification (RFID) tags to provide a global reference [59.82]. This general approach is what formed the basis for one of the first truly commercial autonomous LHD systems, which is now offered as a product by Caterpillar Inc. (see the following). However, the main drawback to this technology is that it relies on classifying tunnel and intersection topology. As roboticists know, misclassifications can happen in practice.


Inspired by advances in mobile robotics research, some considered the application of alternative map-based localization algorithms – the idea being to match sensor measurements to a map rather than by classifying tunnel topology [59.83, 84]. In most cases, a planar poly-line representation of the mine was used to help the vehicle navigate. This is the approach taken by Sandvik AB in their commercial offering. More recently, Atlas Copco Rock Drills AB entered the underground automation game by applying an approach similar in philosophy, which generates sequences of occupancy grid maps and subsequently uses these to estimate the vehicle's position in real time by way of an

unscented Kalman filter (UKF)-based algorithm [59.85, 86].

### Vehicle Control

A machine control system capable of performing at or better than a human operator is necessary in order for robotic tramping systems to compete in industry with manual operation. Many researchers have proposed articulated vehicle steering controllers based solely on vehicle kinematics [59.87–90], while few have considered dynamics [59.91]. Others have contended that wheel slip is significant and should be explicitly accounted for [59.92]. The paper [59.86] describes a control architecture and implementation that permits high-speed tramping by handling hydraulic vehicle steering and driveline dynamics by explicitly forcing a bandwidth separation between low-level machine/actuator dynamics and the path-tracking control problem, which is solved at the kinematic level.

### Commercial Products

Although product descriptions are not the primary focus of this chapter, it is worth briefly mentioning that there are (at the time of writing) three main commercially available underground vehicle automation products: Caterpillar MineStar system for underground [59.93], Sandvik AutoMine [59.94], and the Atlas Copco ST14 ARV [59.85] ( VIDEO 142).

Mobile equipment vendors, not third-party suppliers, sell all three. All three systems are infrastructure free. They all operate by scanning the vehicle's local environment with a 2-D SICK laser rangefinder and combining this data with wheel encoder information. All three systems operate in conjunction with a high-

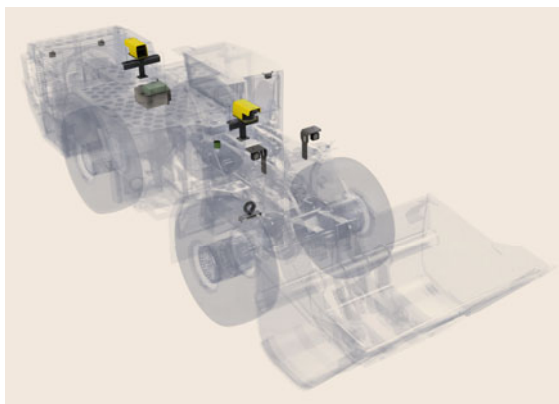
speed wireless network. What is more also all perform autonomous dumping. A schematic of the Atlas Copco product is shown in Fig. 59.15, highlighting the sensor and control components used for robotic tramping.

### 59.3.3 Robotic Loading

Despite a significant amount of research effort in the field of robotic excavation, none has yet resulted in the widespread development or adoption of autonomous or semi-autonomous excavation technologies in the mining industry. Although this section focuses on loading from an underground mining perspective, robotic loading is also applicable to surface mining operations (Sect. 59.2.3).

Robotic excavation is especially challenging because of the dynamic and unpredictable nature of the bucket-rock interactions. Also, a dig controller must manage not only the motion of the excavation arms (e.g., boom and bucket links), but also the penetration rate as determined by the motion of the mobile platform. As a result, performance is highly influenced by the conditions of interaction between the machine and its environment. For example, the forces that act on a bucket as it is actuated to penetrate a rock pile may vary significantly depending upon the properties of the media (e.g., density and hardness), the rock pile geometry, and the distribution of particle sizes and shapes [59.95, p. 562].

It is important to distinguish between excavation in homogeneous materials, such as soil, sand, or regolith, and the challenge of excavating fragmented rock as in mining, which usually has a significant distribution of particle sizes. Fragmented rock may consist of both *finer* (i.e., very small particle



**Fig. 59.15** Scooptram (or LHD) components for robotic tramping, including SICK scanning laser rangefinders (front and rear), articulation angle encoder, drive shaft encoder, onboard cameras, and computing subsystems (courtesy of Atlas Copco, 2009)



**Fig. 59.16** EJC 9T LHD machine conducting robotic excavation experiments in fragmented rock at the engineering facilities of Sandvik Mining and Construction Canada, Burlington, Ontario (courtesy of Joshua Marshall, 2000)



cles), *oversize* (i.e., particles too large for the excavation tool), and a range of sizes in between. Figure 59.16 shows an EJC 9T LHD machine conducting robotic digging experiments in fragmented rock.

The robotic loading problem can be split into two fundamental tasks [59.96]:

1. Dig planning
2. Dig execution and control.

Dig planning constitutes the problem of deciding where and what to dig, possibly considering the geometry of the rock pile, the distribution of particles, and the physical characteristics of the loader and bucket. Dig control refers to algorithms for modifying plans based on the nature of the media encountered, so as to efficiently fill the loader's bucket. This task of the problem is particularly challenging in fragmented rock.

#### Dig Planning

Machine vision has been proposed as an enabling technology for dig planning. The paper [59.97] describes a laboratory-scale excavation system that utilized camera data for control and navigation. In [59.98], a scale-model system was built to mimic the motions of an LHD and different loading strategies were developed that depend on sensed information about the rock pile. Similar work, described in [59.99], employed a vision system to obtain images of the rock pile. In their approach, these images were used to plan the excavation task based on an estimated contour of the rock pile. In more recent work, the authors of [59.100] conducted an experimental study of two novel approaches for selecting an attack pose from 3-D data, with the objective of eventually using this for the robotic loading of sand.

#### Dig Execution and Control

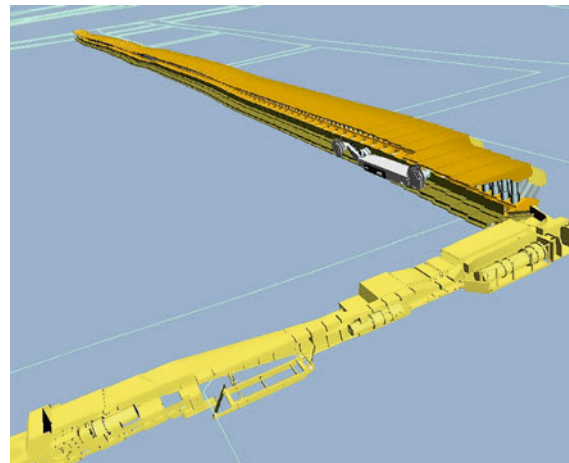
The dig execution and control tasks have been tackled by several robotics researchers during the past two decades. Much of this work has targeted surface mining applications (Sect 59.2.3), although some concepts are transferrable to underground. Targeting underground, in [59.101] it was suggested that the trajectory of an excavator's bucket through the rock pile should not have priority in a devised control scheme, since the objective is to effectively fill the bucket, not to follow a predetermined path. This was explored further in [59.46, 95], which proposed an algorithm for robotic digging that would respond to bucket–rock interaction forces sensed as changing pressures the excavators bucket cylinder by commanding a change in the cylinders retraction velocity, rather than its position. This strategy was based

on full-scale experiments with an LHD. Together with Atlas Copco AB, researchers at Queen's University in Kingston, Canada have recently demonstrated this admittance-based robotic loading strategy by way of full-scale experiments on a modified Kubota loader (on surface) and an ST14 LHD (underground), as shown in [VIDEO 718](#).

### 59.3.4 Longwall Automation

*Longwall mining* is one of the main extraction methods for underground coal mining. This method is highly efficient in cases where thick seam reserves are present, with high-quality coal at shallow depth and benign geological conditions [59.102]. In the longwall process, a *shearer* – a machine with large rotating cutting drums – is driven back and forth across the seam, with each pass taking a massive slice of coal.

Figure 59.17 shows a schematic representation of a longwall mining equipment installation. Two long, horizontal and permanent tunnels known as *gate roads* are cut into a coal seam to form the main boundaries for a large rectangular block of coal, known as a longwall panel. The shearer travels in this panel 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 re-support the roof [59.2].



**Fig. 59.17** Schematic of a longwall mining equipment installation (courtesy of CSIRO, 2008)

A concerted effort to deliver automation solutions for longwall mining saw the establishment of the Longwall Automation Steering Committee (LASC) in 2000, comprising Australian Coal Association Research Program (ACARP) industry representatives, equipment manufacturers, research providers and mine safety authorities. With funding from ACARP, CSIRO and the Cooperative Research Centre for Mining Technology and Equipment (CMTE), now CRC Mining, embarked in a major project to deliver automation solutions for coal cutting and loading, maintaining face geometry and manipulating roof supports without human intervention.

Three issues were identified as critical for longwall automation [59.103]: Face alignment, horizon control, and creep control. Until recently, efforts to develop automatic controllers for face alignment were hindered by the lack of an automatic and reliable method for measuring the actual geometric profile of the longwall face. The solution provided in this project employed a high-end inertial navigation system to provide accurate shearer position and attitude information in real time. The system is shearer-mounted and is referred to as the Shearer Position Measurement System (SPMS). One of the major outcomes of this project was the development of open specifications for the SPMS, and as a direct result, all the major longwall equipment manufacturers now offer automatic face alignment systems.

The second significant technological challenge tackled by LASC was achieving enhanced horizon control (EHC). While face alignment occurs in the horizontal plane, horizon control occurs in the vertical plane, and is significantly more difficult. In order to maximize the extraction of coal and minimize the extraction of waste, the roof and floor cutting horizons need to stay within the coal seam. The EHC incorporates two independent horizon controllers: one for the floor and one for the roof. The set points for the two controllers are generated by an integrated cut model, which sits at the core of the EHC. The cut model incorporates real-time information from navigation sensors, coal interface detectors, seam tracking sensors, as well as off-line geological and geotechnical information.

Finally, *creep control* refers to maintaining the lateral position of the longwall equipment in the panel. As the longwall mining system progresses, the assembly of supports should not creep toward either of the two gate roads. The LASC solution measures creep using laser range finders that scan in a horizontal plane in the panel and roadway directions. The creep information is provided to the longwall shearer automation processing system and generates corrections in the face

profile in the form of a lead to either of the gate ends [59.103].

### 59.3.5 Robotic Explosives Loading

Many tasks in mining and construction require the driving of horizontal and inclined tunnels (or *drifts*) by drilling and blasting for rock fragmentation. Currently, drilling and blasting also remains the primary method for recovering ore from blocks (or *stopes*) in underground hard-rock mining. Blasting engineers design a blast hole pattern that specifies the size and location of the holes in order to achieve the desired rock fragmentation and minimize the damage to the rock mass left behind.

Blast hole charging is a two-step operation. In the first step, the operator places a primer assembly at the end of a flexible hose, inserts the hose into the blast hole, and pushes the hose until the primer reaches the end of the hole. A *primer* is a compact device containing high strength, sensitive explosives used to safely initiate the main column in the blast hole at a controlled time provided by the detonator. Initiation requires electric energy, usually delivered by detonating cords. The hole pushing is mechanized. In step two, an explosive emulsion is pumped into the hole through a hose, the hose is retracted as the explosive gradually fills the hole, leaving the trailing detonator wire. Once a ring of blast holes is filled, the detonator wires are joined and the rock is blasted.

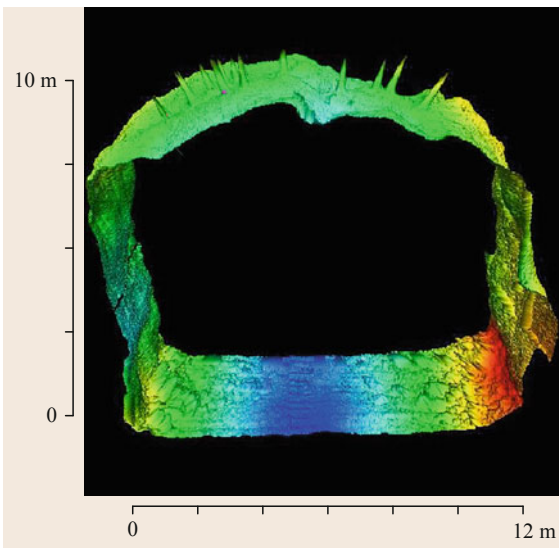
A robotic explosive charging system (RECS) developed by the CSIRO [59.104] incorporates technologies that make the operation of loading holes safer with comparable or better productivity than otherwise possible. The system incorporates mixed teleoperation and robotic capabilities that allow the operator to load the entire pattern from the comfort and safety of the cab of the loading truck. The prototype RECS was developed for a mechanical manipulator derived from a Palfinger truck crane. The system is able to locate blast holes using the laser rangefinder attached to the arm end effector. An automatic arm pose control function is used to achieve a sweeping motion of the arm, during which the laser rangefinder collects images of the tunnel. These images are subsequently processed to extract blast hole locations, and presented to the operator via a human-machine interface.

Once the holes are identified in the scan, they are matched with the holes present in the blast plan and the operator is ready to proceed with the charging. The robot arm is sequenced to pick up the primer assembly from a magazine, and transfers it to the hole. The primer ends up at a pre-set offset from the

hole collar. In teleoperation mode the operator uses in-cab joysticks to insert the primer and the hose in the hole. The video system provides the operator with real-time video images of the relative positioning between the tip of the end effector and the blast hole collar.

In the work of [59.104], hole identification was carried out for 89 and 102 mm blast holes. While the hole diameter is used as a parameter in the identification algorithm, determining the hole length was not a requirement (this is not to say that in-situ validation of drilled versus planned is not important). During scanning, the robotic arm moves the end effector back and forth through the tunnel. The end effector is sequentially rotated, such that the laser is capable of scanning a full 360° pattern in the tunnel. Successful hole detection is influenced by the relative alignment between the laser beam and the hole axis. The larger the misalignment, the greater the chance of generating a false negative. Figure 59.18 shows a typical 3-D profile used for hole identification.

Visual servoing requires locating the tool in relation to the target hole. Cameras mounted on the end effector provide estimates of the location of blast holes with respect to the end effector. The control methodology does not require extensive knowledge of the manipulator physical parameters, and uses a minimal set of tuning parameters, to allow operators to make adjustments if and when required. However, finding an adequate solution raises a number of significant challenges when using a typical truck crane as a robotic arm.



**Fig. 59.18** A 3-D tunnel profile generated for identifying blast holes in a tunnel (courtesy of CSIRO, 2006)

### 59.3.6 Underground Mapping, Surveying, and Positioning

Mapping, surveying, and real-time equipment positioning are core services in many industries, and mining is no exception. In surface mining, the advent of the satellite-based GPS in the 1980s led to fundamental changes in the way everyday operations are carried out [59.105], with new applications being developed even more recently (Sect. 59.2). Based on GNSS, accurate site surveys, information systems, and robotic tools that enhance safety, improve productivity, and cost-saving maintenance operations, for example, have become commonplace in surface mining [59.1, 106].

However, similar progress has been made more slowly in underground mining because no directly comparable positioning technology currently exists for the accurate and real-time localization of mobile equipment in underground mining operations. This section discusses some tools and techniques from the field of robotics that have found their way into mining for such purposes as surveying, mapping, and equipment localization.

#### Underground Mapping and Surveying

At present, manually generated survey maps in mining are used for the design and construction of structures, ventilation, power, drainage, haulage planning, and tracking of development and ore extraction progress [59.107]. However, traditional surveying techniques are slow and laborious, involving many manual steps, infrastructure installation (e.g., retroreflective markers), and repeated measurements to obtain the necessary accuracy for the given application. Conventional survey maps are invariably a coarse approximation of the actual mine structure because, while individual observations may be accurate, few measurements are taken (i.e., poor resolution). Also, surveying is a regulated practice; thus the use of new techniques from robotics requires that current standards be updated.

Several recent advances out of the robotic mapping community show promise for applications in underground mining, and we mention just a select few here as examples. Authors from Carnegie Mellon University (CMU) [59.108, 109] describe robotic systems developed for acquiring volumetric maps of underground mine workings; specifically abandoned mines where ground conditions may be hazardous. SLAM results, based on data from 2-D scanning laser rangefinders, were reported from data obtained in two mines: a research mine in Bruceton, PA, and an abandoned coal mine in Burgettstown, PA.



**Fig. 59.19** 3-D SLAM-generated map of a decline at the Northparkes mine (after [59.112]); the gaps on the floor and ceiling are due to the blindspot between two vertically oriented SICK laser rangefinders; electrical cables can be seen along the left side wall (courtesy of So Jung Yun, 2012)

Some have developed techniques for robotic exploration and topological mapping [59.110] by focusing on the detection and matching of underground mine tunnel intersections as a basis for the creation of topological maps.

New scan registration techniques, such as 3-D-NDT (three-dimensional normal distributions transform) [59.111], have also been conceived specifically for underground mine mapping. Authors from the AASS in Sweden compared their results with the popular iterative closest point (ICP) algorithm on actual mine data.

Recently, researchers at CSIRO [59.112] demonstrated a 3-D SLAM solution, consisting of a spinning 2-D scanning laser rangefinder and industrial-grade micro-electromechanical system (MEMS) inertial measurement unit (IMU). The system was mounted on a site vehicle at the Northparkes mine (Parkes, NSW) that continuously acquired data at typical mine driving speeds. The deployed system mapped over 17 km of mine tunnels in under two hours, resulting in a dense and accurate geo-referenced 3-D surface model. Figure 59.19 shows an example of the generated surface model.

### Underground Positioning and Tracking

The satellite-based GPS uses radio frequency signals that cannot usefully penetrate significant obstacles (e.g., rock); see any reference on the fundamentals of GPS [59.113, 114]. Although high-sensitivity receivers are being developed [59.114], these will almost certainly not function underground. For buildings, some have proposed the use of signal repeaters [59.115], but this is again not practical for most underground mine environments. These challenges necessitate a different approach for underground mines.

As a result, several alternatives for underground mining have appeared in recent years, many of which have limited functionality or are, as of yet, unproven. A recent summary, found in [59.116], presents a survey of the most commonly cited approaches:

- Employing RFID tags for event-based tracking of equipment and personnel [59.117].
- Use of radio signals (e.g., installed Wi-Fi access points) for signal strength-based positioning [59.118, 119], which is very difficult in underground mines due to severe multipath and shadowing, as well as non-line-of-sight propagation and the need for too many devices in order to obtain GPS-like accuracies.
- Dead reckoning using inertial sensors (e.g., IMUs) and odometry for only short-term machine tracking.
- Rock-penetrating very low frequency electromagnetic signals, generally limited to near surface (< 200 m) [59.120] with questionable accuracy [59.121].

However, none of these options yet offer a solution comparable to that provided by GNSS on surface. Another issue is that mining practitioners often do not appreciate the technical limitations of these approaches [59.116, 122]. As a result, some have recently proposed the adaptation of map-based localization techniques for underground mining equipment. For example, [59.123] describes a method for large-scale mapping that employs a combination of RFID tags (as landmarks) and occupancy grid mapping specifically designed to facilitate real-time underground vehicle localization.

## 59.4 Challenges and Industry Acceptance

Despite the latest uptake of robotics technologies in mining, significant challenges remain. Next, we briefly review the most significant ones that are likely to affect the diffusion rate of autonomous systems in mining.

### 59.4.1 Technological Challenges

One expression that describes the current situation of robotics in mining is *islands of automation*. This re-

flects the significant integration issues that exist in relation to fully autonomous and mixed autonomous-manual/remote equipment. The root cause of the problem is a lack of standards to which the various equipment manufacturers should align. Although steps are now being taken to develop these standards (Sect. 59.5.3), the situation is likely to persist for a number of years. In addition to the time it will take to develop the required standards, there will be a significant lag at the equipment manufacturers' end, associated with the rolling out of new products that align with these new standards.

Other challenges to the implementation of robotics technology in mining include:

- Reliability, availability, and fail-safe operation with graceful failure
- Ability to sustain productivity at current or better levels
- Mining in extreme environments and difficulties in developing the required supporting infrastructure
- Current design methodologies for mines and mining systems are not geared to support robotic systems
- Deploying systems in the field and the fact that every mine is different
- Provision of technical support, shortfall in skilled labor, lack of adequate training
- Poorly designed or challenging man-machine interfaces.

## 59.5 Challenges, Outlook, and Conclusion

This section briefly summarizes some of the primary challenges for robotics in mining, as well as examines some emerging themes within the field of mining robotics, beginning with those on the Earth and followed by a short discussion about planetary exploration and extra-terrestrial mining, all of which will rely heavily on robotic tools. The section ends with a short conclusion about the future outlook for mining robotics.

### 59.5.1 Technical Challenges

Despite the recent uptake of robotics technologies in mining, significant challenges remain. One expression that could be used to describe the current status of robotics in mining is *islands of automation*. This reflects the significant integration issues that exist in relation to fully autonomous, as well as mixed autonomous/manual/remote robotic equipment. One specific challenge, for example, is the lack of standards to which the various equipment manufacturers and technology developers should align. Although,

### 59.4.2 Socioeconomic Challenges

The resource industry has a conservative history, and the implementation of new technology and processes must overcome significant inertia. In general, the attitude of people, from those at the working face to senior managers and company executives, mirrors the attitude of the workforce in the manufacturing industry in the early days of industrial robotics; i.e., skepticism about technology and fear of losing one's job. The generational change is likely to alleviate the fear of technology, but robots will be regarded by many in the workforce as a *competitor* for years to come.

Some researchers in human factors also point to the over-reliance on the technology by operators as a possible outcome of spreading robotic systems in the industry. As a common trend across several domains, it was noted that automation and new technologies can sometimes result in operators engaging in more risky behaviours in automated systems [59.124].

Legal issues and insurance are two other factors that could create significant headwinds to the rapid proliferation of autonomous systems in mining or in other civilian activity for that matter. Actuarial analysis is very hard to do for a green field, such as commercial autonomous operations.

steps are now being taken to develop these standards (Sect. 59.5.3), it may take some time before equipment manufacturers roll out commercial products that adhere to these standards.

Some other key challenges for mining robotics include:

- Reliability, availability, and fail-safe operation with graceful and safe failure modes for very large equipment and (often) electric or hydraulically actuated equipment.
- Ability to sustain productivity at current or better levels when compared with current methods and systems.
- Mining in extreme and unstructured environments (e.g., far north, very deep underground, in harsh weather) and the difficulties in developing and supporting the necessary infrastructure in these environments.
- Current mining methods and design methodologies need to evolve so as to inherently incorporate robotic systems.

- Field robotics deployment challenges and the fact that every mine is different.
- Provision of technical support in remote areas, shortages of skilled labor, and the need to re-train existing personnel.
- Developing effective man–machine interfaces.
- Safely managing the colocation of robotic machines and human workers.

### 59.5.2 Socio-Economic Challenges

For the most part, the resource industry has a conservative history and the implementation of new technologies and processes must often overcome significant resistance to change. In many cases, the attitudes of people – from those at the working face to senior managers and company executives – mirror the attitudes of the workforce in the manufacturing industry in the early days of industrial robotics; i. e., skepticism about technology and fear of losing one’s job. However, generational changes are likely to alleviate these challenges.

Some researchers in human factors engineering also point to the risk of over-reliance on technology by operators as a possible negative outcome of the proliferation of robotic systems. As a common trend across several domains, it was noted that automation and new technologies can sometimes result in operators engaging in more risky behaviours [59.124], which would not be looked favorably upon in mining.

### 59.5.3 Emerging Frontiers

There are several emerging frontiers for mining robotics, from the creation of standards to robots that improve safety in mining, and future-looking robots for mining asteroids and other extra-terrestrial bodies.

#### Emerging Standards for Mining Robotics and Automation

Due to the increasing prevalence of automation in mining, there is an immediate need to formulate standards for robotic equipment such that data may be exchanged freely among systems developed by different manufacturers. Currently, a tension exists between manufacturers, for whom it may seem the commercial imperative to design *closed* vertically integrated systems, and the mine operators, who would like any system they purchase to interoperate with all existing items of equipment.

There currently exists a data interchange standard known as the International Rock Excavation Data Exchange Standard (IREDES) [59.125]. This standard

uses the extensible markup language (XML) to define a three-level architecture:

1. Administration level that defines reusable data objects such as coordinate systems
2. Application profile level that covers general information for one application purpose
3. Equipment profile level that has detailed equipment specific information.

The IREDES standard currently covers drill rigs and LHD machines, with many prospective application profiles under active development.

There is also an ISO (International Organization for Standardization) standard called *Earth-moving machinery – Autonomous machine safety* (ISO 17757) [59.126] currently under active development. However, at the time of writing, there is no public information regarding this standard apart from its December 2012 approval. The standard will likely cover the risks inherent in large equipment automation, and common ways that those risks can be mitigated through design and/or procedure.

It is still early days for the standardization of autonomous mining machines, and current efforts are far from complete. However, it is a worthy goal, and one which will only increase in importance as more mining equipment is automated.

#### Mine Rescue Robots

Mining is inherently risky. Although infrequent today, many fatalities have occurred in mining and the necessity of a mine rescue strategy at every operation – particularly in underground mining – is clear. So why not use robots to assist with mine rescue?

Although not mainstream, mine rescue robots have been under development at a few research institutions, including at Sandia National Laboratories where researchers have focused on coal mines under funding from the United States National Institute for Occupational Safety and Health (NIOSH) [59.127]. In coal mining, the risk of explosions is high and poisonous gases may be present, particularly after a disaster. Their tracked Gemini Scout mine rescue robot is approximately 1.2 m long, equipped with an infrared camera (to see through smoke and dust) and gas sensors that allow rescuers to assess the situation before attempting a rescue.

More about mine rescue robots can be found in [59.128], including reference to the first known mine rescue robot prototype at the CSIRO, called Numbat [59.129].

#### Robotic Undersea Mining

There is a vast body of robotics research related to undersea applications and remotely operated underwater

vehicles (ROVs) (Chap. 51 of this book is dedicated to this topic). However, much of this work does not yet directly target undersea mining. Nevertheless, advances in robotics – specifically computer-based mapping, multivehicle coordination, as well as telerobotic drilling and excavation – are likely to make ocean floor mining a reality in the very near future.

Although the pursuit of marine mining dates back to the 1870s, large-scale operations have not yet been realized at least in part due to technological barriers [59.130]. Today, several venture mining companies, including most notably Vancouver-based Nautilus Minerals Inc. (TSE:NUS), are targeting polymetallic seafloor massive sulphide deposits. However, these resources are only accessible by using ROVs equipped with telerobotic seafloor production tools to disaggregate and collect the rock from the seafloor [59.131]. Thus, robotics is poised to play a significant role in undersea mining.

### Planetary Exploration and Mining

Perhaps the next great frontier for mining is that of planetary exploration and resource extraction, whether for in-situ resource utilization (e.g., toward development of the Moon) or for return to the Earth (e.g., mining of asteroids for valuable materials).

Several enabling technologies that support autonomous off-world robotic excavation for large-scale habitat construction and resource extraction have already been developed. For example, researchers from the National Aeronautics and Space Administration (NASA) and CSIRO demonstrated remote excavation of a trench as an example of site preparation and regolith mining [59.132]. This remote excavation system consisted of a 1/7-th scale dragline excavator located at a CSIRO test facility in Australia, a control interface located at a NASA facility in the United States, and a communication network between the two. The tested use case scenario involved remote initiation of terrain mapping, and a click-to-dig user interface that allowed the specification of material transfer in terms of dig and dump points on the acquired terrain map. The terrain map was used to generate a collision-free




terrain-skimming path from dig to dump. The onboard path planner generated a bucket trajectory that included engaging the dig face (bank), filling the bucket and disengaging the bank. Tool force sensing was used as an input to the planner in order to constrain the dig speed and dig trajectory to remain within the operational limits of the machine and ensure adequate material flow into the bucket. The system successfully completed 50 consecutive cycles without any operator intervention. The average cycle time was approximately 63 s with the entire mission taking 52 min to complete.

There is also a thriving space exploration community, particularly within the mobile robotics community, and there is a complete chapter of this book dedicated to space robotics, Chap. 55. However, it is worth mentioning here that mining and planetary resource extraction have much in common and there is increasing cooperation between planetary geologists, mining equipment suppliers, and roboticists in problems related to Lunar and Mars exploration (e.g., see [59.4, 5, 133] and references therein for examples). Moreover, new commercial ventures, such as the widely publicized Planetary Resources, Inc., have been established with the aim of pursuing commercial extra-terrestrial resource discovery and utilization.

### 59.5.4 Conclusion

The desire to improve productivity, safety, and lower the costs of mining is a key motivator for the use of robotics in the mining industry. As highlighted in this chapter, several robotics-related advances have been made in recent history, for both surface and underground mining environments and, after a long courting period with robotics and automation, many mining companies are embracing robotics as a credible and practical tool. Moreover, with the emergence of *field robotics* as an increasingly popular subfield within the robotics research community, as well as the recent formation of networks, centers, and institutes that focus specifically on field robotics (some on mining), the domain of mining robotics appears poised to undergo accelerated growth on the Earth, undersea, and beyond.

### Video-References

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