CHAPTER 9.8

Automation and Robotics

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INTRODUCTION

The need to improve the productivity, safety, and profitability of mining is driving the widespread application of automation technologies in mines. Automation in its many forms is something that miners interact with on a daily basis but may be unaware of its existence. The current implementation of mining automation and robotics has not yet significantly changed mining processes. It has, however, begun to demonstrate its potential value to improve the productivity and safety of these mining processes and associated unit operations. This has lead to a growing vision within the industry that fully automated/robotic mining will be a major part of mining in the near future. This vision includes mines that have the following capabilities:

- Automated personnel and equipment tracking
- Automated materials handling—trucks, loaders, conveyors, sizers
- Smart drills—automated drilling of holes and recognition of material characteristics
- Accurate and automated movement and positioning of all mining equipment
- Automated mechanical mining systems
- Remote supervision from distant locations
- Intelligent and integrated control over all mining processes to optimize resource value

Benefits of Mining Automation

Why does this vision of a fully autonomous mine exist today? Traditionally, the main perceived benefits for introducing mining automation have been

- Improved safety—Removing operators from hazardous and stressful mining environments;
- Higher productivity—Through the improved performance of individual machines (more metric tons per hour) and reduced downtime (automated machines see less duty than human-operated machines); and
- Reduced labor costs—Automation removes operators from machines. Penman (2002) suggests labor accounts for approximately 20% of the cost of operating a large haul truck.

Although these benefits are still appropriate today, the current renewed interest in automation and robotics in mining is related to the following perceived additional benefits:

- Limiting operational variance. Automation allows machines to be controlled so that their output is well defined. For example, an automated shovel would load more consistent bucket payloads. This allows a truck size to be selected for the shovel that will be consistently loaded to its target payload.
- Improved precision. Automation means mining tasks are executed at their planned locations and times. For example, an automated blasthole drill will drill blastholes at their precise location and specified depth as designated by the blast pattern (Holmes 2006). This means the outcomes of blasts are more consistent and generate the desired rock fragmentation, which has significant downstream benefits.

The more significant benefit of limiting operational variance and improved precision is that they enable production consistency. This means that mine designs and, more specifically, mine plans, as well as production and schedules can be generated where there is a valid expectation that they can be achieved. Automation allows mining processes to be controlled more effectively (more like manufacturing facilities) where individual processes as well as the complete mining process can be optimized. The introduction of automation is expected to serve as a catalyst for new credos for mining similar to those that have evolved through introduction of total quality management methodologies to manufacturing.

Definitions

To understand what mining automation and robotics are and what potential impact they have on mining operations, it is important to define the basic terms:

- **Mechanized:** Operations performed by machines
- **Automatic:** Does not make decisions but completes task by following well-defined rules
- **Semiautomatic:** Partly automatic and partly manually controlled

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- **Automation:** Mining tasks completed by machines without human workers
- **Autonomous:** Functions independently without human supervision
- **Robotics:** Machines with high-level capabilities to sense and reason about their environment. Such machines are required for successful automation of tasks in high variable and unpredictable mining environments.
- **Intelligent:** Machines with the ability to learn, understand, and deal with new situations

What Makes Mining Automation Challenging?

Automation is used extensively in many other industries and has demonstrated great value in improving productivity (Gaimon 1985; Carlsson 1995). Its successful use in the manufacturing sector is in the automation of well-defined manufacturing cycles of identical components in a well-known and well-structured environment. Mining is typically conducted as a series of discrete steps, or unit operations, by groups of equipment types working in tandem, such as drilling, blasting, loading, hauling, ground control, and materials processing. Here the highly variable and unpredictable mining environment affects the successful execution of each or sequences of unit operations. Thus, automated mining systems must be able to sense, reason, and adapt to this unpredictable environment in order to function effectively. In addition, these systems need to operate for 365 days per year in very harsh mining environments. For these reasons, many existing automation technologies from other industries are not readily transferred into mining.

The growth of robotics, driven primarily by the military, has provided the tools necessary to develop autonomous mining systems. These developments have been driven by low-cost increases in computing power; new algorithms for signal processing, perception, and control; and in particular, new sensing technologies such as Global Positioning Systems (GPSs) and radar and laser systems (Durrant-Whyte 2009). These tools are essential to accurately locate, control, and coordinate the activities of robotic machines. Onboard sensors can generate real-time maps of the mine environment (geometry and geology) around these machines so they can be optimally controlled. This spatial control information is essential to plan and schedule the complete mining process (including machines). This will make mining operations more precise and predictable (like a factory) and ultimately dramatically more productive.

Fully autonomous mining that encompasses the complete spectrum of mining processes will be expensive and require significant technical development. More importantly, it will only be achieved through significant change management of mining culture to accept these innovations. Mine automation technologies will achieve the highest probability of success using a multistep implementation program. The resulting early introduction of technologies can provide mining benefits such as

- Operator aids that improve machine performance and reduce machine damage,
- Improved mine sensing systems that can provide managers with better information about the state of the mine,
- New mine models that allow managers to execute operational decisions,
- Semiautonomous and remote-control capabilities that remove operators to safer environments, and
- Collision-avoidance technologies that prevent accidents.

Mining Robotics—The Science

Field robotics is now well established in the research, commercial, and military arenas. Mining robotics is a stream or application within field robotics. The basic science (with associate sensors, computing hardware, etc.) that drives the technology in this field is not being developed by the mining industry; however, mining robotics is using and reengineering this technology. Several good textbooks and journals explore the extensive science and technology of field robotics. Buehler et al. (2010), Siegwart and Nourbakhsh (2004), Everett (1995), and Ge (2006) are excellent references for more detailed information.

Evidence of the close link between researchers in field robotics and mining equipment manufacturers is Caterpillar's sponsorship of the Carnegie Mellon University (CMU) participation in the Defense Advanced Research Projects Agency (DARPA) Grand Challenge competition. This competition tests the performance of autonomous ground vehicles in a series of different outdoor environments and demonstrates the state of the art in mobile robotics. CMU won the last competition in 2007 and has been in a longstanding partnership with Caterpillar to develop automated mining equipment (Binning 2009).

A very large body of basic research into the development of autonomous vehicles includes major themes such as route planning (Al-Hasan and Vachtsevanos 2002; Frazzoli et al. 2002; Salichs and Moreno 2000); obstacle detection and avoidance (Azouaoui and Chohra 2002); close maneuvering strategies (Gomez-Bravo et al. 2001); and autonomous vehicle control system design (Pereira 2001).

MINING AUTOMATION AND ROBOTICS IN PRACTICE

This section provides an overview of selected automation solutions for the mining industry. Some are commercially available, others are being trialed at mine sites as precommercial technologies, and some are still in the research and development (R&D) stage. Detailed published information about many of these systems is difficult to find as manufacturers and mines are reluctant to release information that might hurt their competitive advantage.

Autonomous Haulage Systems—Technology

Autonomous haulage systems are generally divided into two major divisions: site-level systems, sometimes called the office site manager, and machine-level systems, sometimes called the onboard controls.

Site-Level Automation

The site-level systems provide an interface between the human (and software-based) mine planners, provide data for business tracking, and provide optimization and control over the haulage system machines. *Mine planning* is defined as determining the goals and priorities and communicating them to the mine management tools, and *mine management* is defined as optimization of existing resources to accomplish the goals.

Mine planning. This requires significant human interaction to set goals such as prioritizing production volume versus cost factors (fuel usage, risk of machine damage) or prioritizing short-term production versus long-term mine efficiency. The challenge in mine planning is to ensure that both explicit and implicit goals are accurately translated to the more automated mine management system.

Mine management. Fortunately, there is a large body of experience with mine management systems. However, a new generation of mine management systems will be required to address the requirements of autonomous systems. The next generation of such systems will require much more detailed mine models and many new features to manage autonomous equipment.

Machine-Level Automation

Machine-level automation requires the ability to

- Understand what tasks need to be accomplished (high-level planning);
- Determine location (positioning);
- Perceive the environment based on the location (perception);
- Based on the environment and position, plan future tasks to achieve the desired goals (task-level planning);
- Execute the planned primitives (primitive execution); and
- Handle exceptions.

High-level planning. High-level planning is the ability to interpret directions from the mine management system and to select the appropriate behaviors. For example, if an autonomous truck is directed to a load area, it needs to understand the path, validate the path, and ensure that it has the required behaviors and capability to execute the plan.

Positioning. Positioning is the ability to determine the machine's pose, meaning its location and orientation. For autonomous machines, an accurate reliable pose is critical. Although absolute accuracy is actually not as critical, the ability to accurately register the machine's pose to the mine model is a requirement. Multiple types of positioning must be considered:

- For aboveground applications, the most common real-time kinetic Global Navigation Satellite Systems (RTK GNSSs) are
  - RTK GNSS + machine sensors (such as odometers),
  - RTK GNSS + machine sensors + inertial,
  - RTK GNSS + machine sensors + inertial + perception-based positioning, and
  - RTK GNSS + machine sensors + inertial + pseudolites (ground-based satellites or reference stations).
- For belowground applications, the most common types of positioning systems are
  - Radio frequency (RF) based distance measurement,
  - Perception-based positioning + machine sensors, and
  - Perception-based positioning + machine sensors + inertial.

These positioning systems are well known in the industry. Perception-based positioning systems have been used in restricted environments such as factory settings for more than two decades (Caterpillar 1991) and in underground mining applications for nearly a decade (Ferret 2003). RTK GNSS-based positioning systems have been used to provide centimeter-level accuracy in construction applications for a decade (Saghravani et al. 2009). RTK GNSSs are susceptible to poor GNSS coverage and must be augmented to provide very high levels of availability. Unfortunately, specific areas (near the poles) and areas with blockage to the east and west can have significant problems with GNSS coverage. However, governments around the world have pledged strong support to the GNSS infrastructure; and as more satellites are put in service, the GNSS coverage should continue to increase substantially. The most well-proven technology to augment GNSS for short durations is using inertial sensors plus odometry. Unfortunately, this technology only has short-duration accuracy. Other possibilities for augmentation include pseudolites, often called ground-based satellites, or RF-ranging beacons. These systems allow individual mines to establish their own ground-based positioning system, which, unfortunately, can be very expensive to install and maintain.

Clearly, the more types of independent positioning sources that are available, the more robust the positioning solutions will be.

Perception. Autonomous machines generally need a good understanding of their surroundings to accomplish object detection and sometimes assist with positioning. The perception system usually requires information from the mine model and the positioning system to accurately determine and report the location of objects. Perception sensors can come in several different forms: radar, laser, vision, and sonar (not discussed here).

Radar has been used since the early 1900s to detect ships and large metal objects. More recently, millimeter-wave radars have been developed to detect objects for adaptive cruise controls and autonomous machines. Radar has the advantages of long range and "seeing" through dust and fog. However, radar suffers from relatively poor resolution when compared to laser-based systems. The size of an object that can be detected depends on the object's radar cross section (RCS), defined as the projected area of a sphere that would return the same signal to the transmitter. The most effective means to increase the effect of RCS is to install corner reflectors. Commercial units are sold for small boats to improve their detection ability by radar. Corner reflectors can be thought of as "tail lights" for radar transmitters.

Laser systems provide the best resolution but suffer from obscurants such as dust and fog. Newer lasers overcome much of this limitation by using multiple reflections from each point or from time gating the return to ensure that small, diffused particles (dust, fog, rain, and snow) do not obscure other objects. As the density of particles increase, the effectiveness of this method diminishes. As with radar, retroreflectors (such as tail lights or reflective tape) can be added to targets to greatly enhance their visibility to laser.

Vision has significant promise for low-cost object detection and object recognition that is most like human perception. There has been a tremendous amount of work in this field and rapid progress is being made, but so far, vision is limited to relatively short-range applications. Vision also is sensitive to shadows, dust, fog, rain, snow, and reflective surfaces (e.g., a reflection in a puddle may be confused as a real object).

Combining multiple spectrums has significant advantages. For example, combining radar and laser gives the longer range and improved penetration of radar with the laser's ability to detect smaller obstacles and improved object classification. As another example, combining laser and vision allowed the TerraMax team (in the Grand Challenge competition mentioned previously) to recognize tumbleweeds in the desert that stumped a vision-only system in earlier tests (Broggi et al. 2010).

Unfortunately, there are currently no practical standardized tests by which to easily determine the capabilities of object-detection systems under all conditions.

Another consideration for the practical use of autonomous systems is that none of the obstacle-detection systems available today have the ability to differentiate a pile of small loose rocks (e.g., a windrow left by a motor grader) from a single large rock that could damage tires.

Task-level planning. Task-level planning is defined as establishing a sequence of task or behaviors to accomplish a goal and is generally rule- or constraint-based. As expected, task planning varies significantly based on the type of goal, the number of constraints, the variability of the environment, and the flexibility of the automated system. One of the common machine-level planning tasks is object avoidance.

Primitive execution. Executing planned primitives is the fundamental machine operation; some examples include drilling, tramming, loading, grading, stability control, dumping, and ripping. These operations generally require continuous closed-loop control and are probably the closest machine operation to a human skill.

Exception handling. Handling exceptions is the ability for an autonomous machine to recognize that it does not have the means or required primitive ability to handle the existing situation, and thus it resorts to fail-safe behavior—usually stopping and asking for help.

The building blocks for autonomous haulage system technology have been developed over the past two decades to the point where commercially viable automation systems for underground mining are now available, and commercially viable haulage systems for surface mines will be available within the next few years. In the near future, autonomous and intelligent remotely operated machines will provide the opportunity for remote operations centers that allow miners to work in the relative comfort and safety of an office environment. These first-generation systems should rapidly evolve to provide continuous improvement in efficiency, productivity, and machine availability.

Autonomous Surface Dump Trucks

One of the principle benefits from using fully automated dump trucks (ADTs) is the direct reduction of labor costs. Penman (2002) found that for two-axle dump trucks in the 220-t (metric tons) class, labor accounts for approximately 25% of operating costs, fuel approximately 45%, and tires approximately 30%. For the larger, 300-plus-t class truck, Penman found the approximate cost split is labor 15%, fuel 30%, and tires 55%. Other benefits include improved safety through the removal of operators from hazardous areas and reductions in machine duty (rate of accumulated damage), and fuel consumption through more consistent operation. For example, the world's first fully automated straddle carrier system at the Port of Brisbane has reduced energy costs per container move by 40% (Kalmar Industries 2007).

The enabling technologies (navigation, truck control, and collision detection) for ADTs exist in a semimature form, and prototype ADTs integrating these technologies have been developed and tested. Commercial ADT systems are not yet available. Of the major haul truck manufacturers, Komatsu and Caterpillar have both developed and demonstrated autonomous dump truck technologies.

Komatsu currently has two sites operating its ADT technology, called FrontRunner. Codelco, at its Gabriela Mistral mine in Chile, has been operating 11 autonomous haul trucks since 1997. More recently, Rio Tinto, at its West Angelas mine in Western Australia, has been operating five trucks since late 2008 (Cribb 2010). Both sites are using 930E-4 electric-drive trucks with a payload of 300 t, and the trials are intended to test autonomous trucks in high-production scenarios. In both cases, the ADTs are not working on the same haul roads with manually driven trucks.

Komatsu's FrontRunner autonomous haulage system operates as a comprehensive fleet management system for mines. The haul trucks are equipped with vehicle controllers, high-precision GPS, obstacle-detection technology, and a wireless network communication system. The system has the capability to navigate a haul route, dump automatically to hoppers or to the ground, and work with some (but not all) loading equipment. The system leverages off several mature technologies, notably the GPS and inertial navigation systems for navigation, and millimeter-wave radar and laser systems for safety and collision detection.

These technologies are integrated using largely fixed automation strategies. Trucks navigate from a so-called pit database, which serves the purpose of a haulage map and contains largely geometrical information, notably the boundaries of the haul road, the truck's travel path, and the boundaries of the loading and dumping areas. The boundaries represent the extent of the ADT's allowed safe operation and are established by driving a light vehicle fitted with high-precision (differential) GPS around the haulage perimeter. The safe-working-area boundaries in load areas are updated as the shovel moves. As an ADT is manually driven along the required haul route at the required speed, the truck's control computer records position, speed, and direction, defining the truck's travel path. The truck's control system (steering, braking, engine, and dumping functions) has the truck "replay" this path to navigate from the load area to the dump zone and back again. The use of the teach–replay approach used in current ADTs simplifies the problem of planning the truck's course or path. The truck doesn't need to plan its path; it knows its path having learned it in the training run. The repeatability of the replayed paths under this approach is high, but it is necessary to add "dither" (a small error in truck path control so that the truck does not always follow the exact same path on the road for every trip, thus causing wear over a broader surface of the road) to the steering action to distribute road wear.

A central control computer manages the ADTs on a particular haul. Each ADT continuously communicates key data (position, speed, and heading) back to the central control computer, which provides general haulage management including tracking each truck's trajectory and anticipating collisions. An onboard safety and collision-avoidance system based on millimeter-wave radar and laser-sensing technologies is used. This system has an overriding authority to bring the truck to a stop if an obstacle or safety hazard is detected.

Automated Underground Loading and Haulage

In underground mines, the restricted environment in which equipment operates has aided in its automation. In addition, some of the greatest potential hazards to miners occur when operating in and around underground mobile equipment. This was an early driver to automate primary underground mobile materials handling equipment. Load-haul-dump units (LHDs) and trucks operating underground follow well-defined routes in repetitive operating cycles. These, coupled with a well-structured underground operating environment, made deployment of early autonomous vehicle technologies feasible. As early as 1988, King (1988) predicted a positive economic return for the use of semiautonomous LHDs. Caterpillar Global Mining (2008) describes recent trials of automated LHDs at the Malmberget mine in Sweden showing an increase in productivity of between 10% and 20%.

Autonomous LHDs and underground trucks are now available from several manufacturers. These are the Caterpillar MineGem system (Caterpillar Global Mining 2008), Sandvik's AutoMine system, and Atlas Copco's Scooptram Automation system. At this time, more than 10 mine sites worldwide are operating or plan to operate either or both autonomous LHDs and underground trucks. These include De Beers' Finsch diamond mine in South Africa (Faurie 2007), Codelco's El Teniente mine in Chile, and the Stalwell gold mine in Australia (Caterpillar 2007).

Both systems have the underlying premise of removing the operator from the machine to a remote operating station, where the machine can be teleoperated. This station could be located underground, on the surface at the mine site, or at some distant location. Operation requires onboard cameras, computer control of machine functions (steering, braking, acceleration, bucket motions [LHDs], etc.), high-speed network communications, and associated safety systems. However, simple teleoperation is stressful for operators and less productive than manual operation.

The solution is operator-assisted automated steering during teleoperation. Here the operator does not physically steer the system but views the machine's location in real time on a mine plan (typically on a computer screen) and then uses a joystick to give the machine the direction of travel. In Caterpillar's MineGem system, this is called copilot mode.

Finally, in autonomous mode the remote operator provides a goal for the machine (LHD or truck) and the self-guidance system controls the vehicle. In Caterpillar's MineGem system this is called autopilot mode. Typically, the operator fills the LHD's bucket in remote mode and then enters autopilot mode to tram to the dump point, empty the bucket, and return to the loading point. Thus, in autopilot mode, several machines can be operated by a single operator. For safety reasons, remotely controlled and autonomous machines need to operate in exclusion zones that strictly control access.

The key to operator-assisted automated steering and autonomous navigation for LHDs and trucks is the use of a laser–radar range-sensing system. This system maps the location of objects (typically walls) around the machine and determines their location by comparing the measured profiles to an existing database provided from the mine map. This technique is known as simultaneous localization and mapping. Thus, knowing the location on the map relative to the nearest walls, the control system can drive the LHD to the desired location.

Automated Dozers

Dozers are typically used for a wide range of applications in mining. These include profile construction, cleanup around other machines, ripping, and utility work. Thus the level of complexity required to automate a dozer is very much a function of the individual task needs, such as the following examples:

- Adjusting ripper depth and angle, and dozer speed and direction, to ensure good ripping performance is key for an automated ripping dozer. Here, interaction with other machines is often limited.
- In many cases, dozers create structured profiles for other machines to work on or from. Here, material movement accuracy may be important.
- Dozers that undertake utility work such as dragging pipes and cables, moving power boxes, and pushing scrapers may have dedicated sensors and automation capabilities. Here, the dozers require the ability to rapidly move from one application to another.
- Interaction with other machines, and detecting where and what to clean up, is important for dozers required to undertake cleanup tasks. An automated dozer would have to detect when and what to clean up and interact with other machines (shovels, trucks, etc.) in a variety of modes.

The automation of dozers to remove operators from machines appears feasible for dozer operations where interactions with other machines is limited, and complex sensing and recognition of subtle changes in the machine's environment are not required. These cases do not require development and use of complex sensing systems, advanced automation infrastructure, or control of complex machine–material interactions.

Automated dozers are not commercially available today. Several original equipment manufacturers (OEMs) and third-party providers have GPS-based dozer operator aids. These include, from Caterpillar for example, "an in-cab display that gives operators easy to understand color diagrams of where to cut and fill. The system uses onboard computers, software, data radios and centimeter-level GPS receivers to constantly monitor work and update the plan" (Caterpillar 2006b). Remote-control solutions have also been available for dozers for many years. These are typically retrofits by third parties.

Research into better solutions for remote-control dozers continues. A recent project funded by the National Institute for Occupational Safety and Health in the United States developed a remote vision system for dozers on coal stockpiles. The project involved Consol Energy and Caterpillar as participants. This work is described in Schiffbauer et al. (2007).

Many of the enabling technologies (dozer control, positioning, and navigation) for automated dozers have been used in remote-control applications for some time and therefore exist in a semimature form. It is expected that automated dozers with the complete capability to build profiles, clean up, and rip will be achievable in the next 5 to 10 years.

Dessureault et al. (2007) and Holmes (2006) describe an automated dozer project at Freeport-McMoRan's San Juan (Arizona, United States) test site. The target application for this dozer is ripping. The dozer sensors include GPS, Sick lasers, and cameras (for teleremote operation).

Automated Blasthole Drills

Automated blasthole drills (ABDs) have the potential to generate a number of benefits. These include

- Reductions in machine duty (rate of accumulated damage) through smoother computer-controlled operations, and

improved blasting performance through more accurate and consistent drilling;
- Reduced labor costs; and
- Improved safety through removal of the operator from a hazardous and dusty environment.

Automation can also optimize drilling performance through control of bit loading, drill rpm, and torque parameters. Increased penetration rates, lower bit wear, and reduced drill costs will result. It is also desirable that holes are drilled at locations specified by the designed blasting pattern. Inaccurate holes can lead to poor blasting fragmentation, inappropriate muck-pile shape for loading, and so on.

ABDs also have the potential to generate benefits that include implementing drill-based, high-level rock recognition systems to provide detailed rock type and structure information that can be used in blast design. Consistent drill operation through computer control of the drilling process enables these systems to operate effectively.

Thus, the enabling technologies (navigation, drill control, and remote control) for ABDs have existed in a reasonably mature form for some time. Prototype ABDs integrating these technologies are currently under development. Holmes (2006) describes the development in 2005 of an automated blasthole drill called the Advanced Rotary Drill Vector Automated Radio Control (ARDVARC). Holmes states, "Preliminary results of ARDVARC trials as compared to normal manual drilling operations has shown a +15% productivity gain, improved pattern and hole quality, and lower machine duty cycle. Additional gains achieved from hole-to-hole positioning are expected." The technology was tested on a BE49R drill but has been transferred to the Atlas Copco PV271 drill.

Rio Tinto has also been developing an automated blasthole drill that is currently operating at its West Angelas iron ore mine. (The outcomes of this project are described in detail later in this chapter.) This machine is designed to drill automatically in both rotary and rotary-percussion modes. In addition, the drill is capable of performing rock recognition during the drilling process in order to build a rock mass description of the area to be blasted. This description is then used in the blast-design process. This drill also has full video remote-control capabilities.

The typical attributes of autonomous blasthole drills currently under development are

- Automatic drilling of the hole from collaring though pipe removal when either manned or autonomous;
- Navigation from hole to hole within a drill pattern;
- Completion of drill pattern autonomously including accurate setup, relocating holes (due to hole failures or impossible collaring), inclined holes, and drill bit changes;
- High-level task instructions from a drill-and-blast management system;
- Monitoring of self-condition (e.g., airflow and pressure, oil pressures, rpm, component failures) and appropriate reaction (e.g., report bit failure back to drill-and-blast management system);
- Monitoring of drill parameters (thrust, rpm, vibration, and other active and passive geosensors) and using this information for rock-recognition information that can be fed into a drill-and-blast design system; and
- Video remote control of all drilling functions.

Remote Operations Centers

A remote operations center (ROC) enables supervision, control, analysis, and data acquisition from afar. In simplest terms, an ROC can be regarded as a platform for enabling process automation and business integration. An ROC enables

- Enhanced occupational health and safety by removing operators and maintainers from risk exposure;
- Reduced labor costs by relocating high-cost, knowledge-intensive labor away from mine sites to urban centers;
- Increased productivity through
  - Identification of inefficiencies at operating interfaces,
  - Collaborative planning between functions (operations, maintenance, and procurement),
  - Sharing of experience and knowledge across mine sites,
  - Process visibility along the process chain; and
- Potential to lock in benefits through knowledge capture and reuse.

Implementing an ROC provides an important catalyst for change within an organization. Current workflow patterns must be evaluated and modified or adapted. Implementing ROCs therefore provides an important stimulus for changing work practices and driving an organization to achieve higher levels of labor productivity.

Interest in applying ROCs is growing within the mining industry. Examples of early adopters within the mining industry are Rio Tinto Iron Ore (RTIO) in Western Australia and Freeport-McMoRan in their Arizona (United States) operations.

Schweikart (2007) outlines the business drivers for RTIO's implementation of an ROC:

- High cost of supporting remote staff
- Desire for increased staff retention
- Business integration
- Faster, better decisions

The ROC will also supervise the autonomous systems operating at RTIO's West Angelas iron ore mine site. A fleet of five autonomous 320-t Komatsu haul trucks are operating at West Angelas, as well as one automated blasthole drill rig (Trounson 2007).

The removal of the need to maintain a large work force on-site saves ancillary camp expenses; remote working allowances; and fly-in/fly-out expenses, which can account for significant costs. Additionally, integration of operations (site, transport, and infrastructure) in one center removes "silo mentality," where people are focused only on the component of the operation they are involved in and fail to see the effects on the whole mining process, creating bottlenecks at interfaces.

Improved telecommunications infrastructure, in particular telephone networks and fiber-optic links, are cited by Dicker (2007) as key technology enablers for the ROC development. RTIO is evaluating the remote support of maintenance personnel via head-mounted displays and wearable computers. Support would make extensive use of video conferencing, remote desktop access, and voice-over IP technologies. RTIO is also evaluating remote collaborative planning via the use of augmented reality (virtual reality based on real sensor information) and touch tables (Schweikart 2007).

Schweikart outlines a 4-year plan to achieve remote-integrated operations. The first step of this plan is to integrate disciplines (planning, operations, and maintenance functions) at site level, and to begin the transfer of people from site to ROC. The second step is integration per asset (site operations integration) through the transition to remote operation and deployment of operations models. The third step is integration across sites. Because of safety concerns and relatively static operating environments, it is likely that ROC technology will be implemented first on fixed assets, such as beneficiation plants.

RTIO is investing particular attention to aspects of change management and reevaluation of workflow. Scweikart emphasizes that changing to a remote supervision and operations model necessitates a change in the way that work and information flow is managed, and that replicating existing workflows may not improve productivity.

Coyle and Holmes (2007) indicate that the installation of Freeport-McMoRan's ROC on-site was justified on the elimination of inefficiencies across operational boundaries. The ROC is also seen as playing an important role in "institutionalizing the knowledge" of maintenance and operations experts. Here, the vision of the future has tactical operations personnel co-located in a "room of truth." Verified information is made available on a real-time basis so that subject-matter experts can assist less-skilled operatives in the field. Crosspollination of ideas and shared operational awareness are forecast to lead to significant efficiency gains for the organization.

Automated Digging

Large-capacity shovels and hydraulic excavators (called diggers in this section) with bucket capacities to 70 m^3 are critical production units at most open-cut mine sites, and there is an ongoing imperative to improve their productivity. Automation is seen as one of the strategies by which improvements can be realized.

The automation of diggers presently stands at an interesting nexus. Most of the technology needed to realize the automated digger exists (albeit at varying levels of maturity), and developments in other sectors, including industrial robotics and the automotive and aerospace industries, are delivering further advances that enhance technical feasibility.

However, the cost and risk of introducing automated diggers to mining operations currently outweighs the perceived benefits. An automated digger must operate as part of the overall operation of a mine with implications on mine infrastructure, operational practice, work-force skills, and site culture. The gap is significant and no mining company is actively pursuing the introduction of automated diggers to their operations, notwithstanding the several significant mine automation initiatives taking place worldwide (e.g., Rio Tinto's Mine of the Future at the West Angelas mine site).

The transition to automated diggers will likely occur over the next 20 years. It will almost certainly be staged through incremental stepping-stone technologies that, in themselves, bring productivity and reliability benefits and allow the risks to be understood and controlled and the technology to mature and be proven and accepted in mining environments.

This section attempts to identify, at a fairly high level, automation capabilities that might serve as planks in the bridge to realizing the autonomous digger over the next two decades.

Capabilities of the Autonomous Digger

The autonomous digger

- Excavates material and loads trucks with minimal human intervention;
- Plans and executes repositioning moves using high-level mission statements referenced to the mine plan;
- Feeds up-to-date information garnered from onboard sensors back to the mine plan including terrain information, material diggability, and productivity indicators;
- Manages the dig face and floor to optimize productivity and maintain favorable bench structure;
- Automatically executes ancillary functions including management of the trailing cable (on electric shovels), machine park-up for access, and so on;
- Has advanced status monitoring capabilities to identify situations associated with the machine or the environment requiring attention. This includes monitoring structural and electrical heath trends for early prognostication of events and failures;
- Manages overall activity in the load area including the scheduling and dispatch of trucks, cleanup activities, and so forth; and
- Provides an information-rich teleoperation mode that allows recovery from exceptional situations to be completed remotely.

Benefits of the Autonomous Digger

The benefits of the automated digger stem from the increased consistency and reduced variation that automation brings to equipment operation, resulting in productivity and reliability improvements and the ability to have the machinery operate under its most favorable conditions. Ultimately this translates to increased productivity with lower production costs and energy consumption.

The business case for the autonomous digger is likely to be built around the following benefits:

- Consistent and accurate loading of haul trucks. When trucks are loaded to their rated payloads and the load is correctly distributed across the tray, then the chassis, transmission, and tire life are significantly improved and operating costs reduced.
- Increased digger availability. Automation brings consistency that stands to increase equipment availability through lower duty loadings.
- Safer operation. Most safety incidents associated with diggers are linked to operator error (e.g., digger–truck collision). By marginalizing the root cause, automation has the potential to reduce the frequency of accidents and near misses.

Technology Gaps

Four broad technology gaps must be bridged to realize the autonomous digger:

1. Control strategies must be developed to enable automated machines to operate interdependently with other equipment (manned and automated).
2. Situational awareness capabilities must evolve to the point where they can replace the many and varied functions

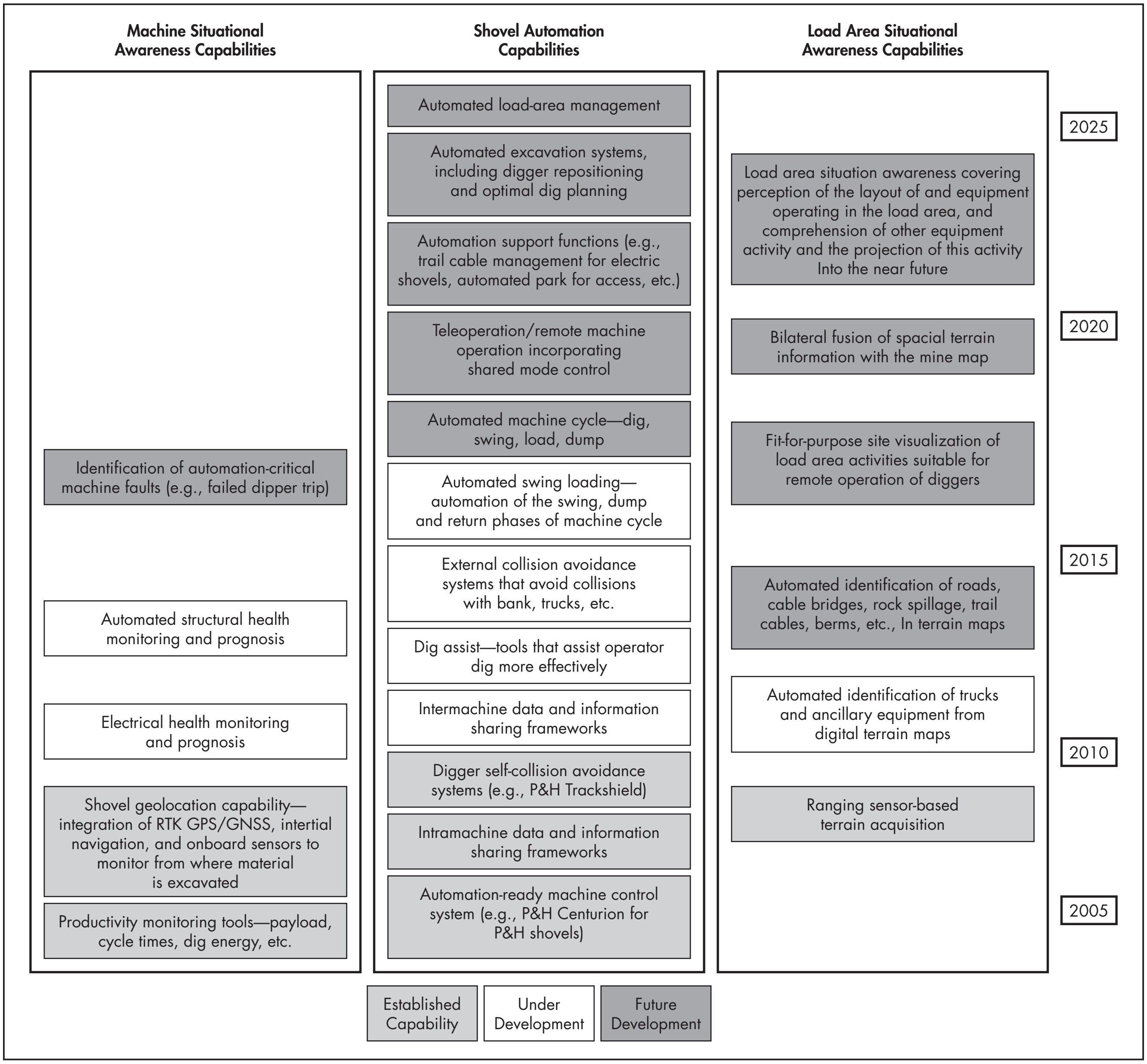


Figure 9.8-1 Autonomous digger capability plan to 2025

currently performed by human operators in planning and actions, and monitoring the status of the machines.

3. Technologies are required that enable effective integration of automated machinery into mine systems.
4. Work-force skills must be enhanced to support deployment of high-end automation technologies.

A significant component of the shovel automation problem is systems integration, including management of interactions with trucks and other equipment and integration of the autonomous shovel into the mine plan. Although in the long term there will, almost certainly, be multiple technology providers working to agreed automation standards, at this time the problem is not sufficiently well defined for effective standardization efforts. The likely scenario for the short-to-medium term is that various equipment and technology providers will integrate their proprietary systems by ad-hoc methods on an as-needed basis under pressure applied by the end user (the mining companies), or one provider will come to dominate the market and set a de facto standard for integration.

The long time horizon for achieving a fully automated digger system mandates a multigenerational technology plan with commercial outcomes that prove technology components and support and maintain the development effort toward its end goal. Figure 9.8-1 gives a digger automation capability plan to 2025 with capabilities divided into three categories:

1. **Machine situational awareness capabilities.** These include such things as machine performance monitoring, functional safety capabilities support automation requirements, electrical and structural health monitoring.

2. **Shovel automation capabilities.** These incrementally build from operator assists such as collision-avoidance tools through automated digging to management of the load area.
3. **Load area situational awareness capabilities.** These build an evolving richer situational awareness model of the load area with knowledge of digger and truck positioning at the lowest level, building toward the full perception of elements in the load area, the comprehension of their meaning, and the projection of their status in the near future.

Implicit in this capability map is that machine and load area situational awareness capabilities feed into shovel-automation capabilities. The timeline is indicative as is the ordering, but it is generally expected that capabilities will flow in this order.

The plan has been organized so that each identified capability could, in principle, serve as a commercialized outcome. The continual delivery of technology products that have productivity or maintenance benefits in their own right and contribute incrementally to the autonomous digger represents the only practical strategy. R&D-based innovation at all levels of the plan is strongly needed, and the most likely scenario is that R&D will be completed by consortiums made up of an equipment manufacturer, the end user, and one or more third-party technology providers including research organizations and universities.

Current State of Automation

Fully automated shovels are not commercially available. However, shovel automation has been the focus of extensive research over the past few years. Dunbabin and Corke (2006) describes automation work completed on a 1/7-scale model cable shovel that demonstrated the ability to automatically perform multiple truck-loading passes that included excavation of the dig face, swinging with obstacle avoidance, identifying an awaiting truck tray, determining an optimal loading strategy, and dumping the material.

McAree et al. (2007) describe collaboration between the Cooperative Research Centre for Mining (CRCMining) and P&H to develop advanced technologies leading toward shovel automation. A P&H/CRCMining laboratory has been set up in a quarry north of Brisbane, Australia, and includes a full-sized P&H 2100BLE electric cable shovel. This laboratory is used to develop and evaluate technologies that increase the productivity of electric mining shovels.

The Australian Coal Association Research Program (ACARP) is currently funding a project to develop, to proof-of-concept, an automated swing-loading technology for electric mining shovels at this facility. A joint CRCMining and Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) team are developing technologies for a shovel that cycles the swing, dump, and return functions. This includes automatically identifying the location of a truck or in-pit crusher–conveyor to be loaded; planning and executing a minimum path from dig to dump location without the dipper colliding with the truck, crusher, or bank; and dumping without spillage and swinging back to tuck position for the next dig.

Automated digging is probably the most complex component of loader automation. Automation technologies to assist digging are commercially available for several of the autonomous LHD products, but not for large-surface loading machines. A considerable body of research in automated digging exists. Singh (1997), Hemami and Hassani (2009), and Lever (2001) provide reviews of this research area.

Longwall Automation

Two basic control systems exist in a longwall operation. One control system operates in the horizontal plane to control the plan-view geometry of the longwall face, and the second operates in the vertical plane to control the roof- and floor-cutting horizons within the coal seam. Added to these functions are systems for armored face conveyor (AFC) control, including chain tensioning and load sharing, and shearer haulage control.

In simplest terms, in plan view, the longwall face should be straight and perpendicular to the gate roads. If the face is straight, both mechanical stresses on the armored face conveyor and roof support geotechnical issues are minimized. The process to achieve this situation is known as face alignment. As the longwall retreats, the assembly of supports should not creep toward either main or tailgates. To achieve this result in practice, often the face line is angled, introducing so-called tailgate lead or lag with respect to the main gate so that in sloping seams, the same creep-minimizing result can be obtained. Managing the lateral position of the longwall equipment in the panel is called creep control. Automatic face alignment and automatic creep control are two functions that can be applied to effectively provide automation of longwall plan view geometry. Available systems are discussed in this section.

In the vertical plane, the automation situation is more complex. The goal of the longwall, similar to any mining operation, is to maximize extraction of product and minimize extraction of waste. This means the longwall shearer should operate so that roof- and floor-cutting horizons are entirely within the seam, or in some cases within a selected band within the seam. Achievement of this goal is known as horizon control. Automated horizon control needs to at least emulate and at best entirely replace human-operator strategies for steering the shearer within the seam. Again, the available automation solutions for horizon control will be discussed.

Undeniably, longwall automation has the potential to deliver significant advantages in both productivity and safety (Henderson 2007). Interruptions to the mining process are basic causes of decreased productivity. Continuous automatic face alignment, for example, can virtually eliminate stoppages caused by current string line–based manual alignment processes, and optimal alignment of AFC components minimizes wear and reduces consequent equipment breakdown or change-out delays. Close control of face geometry can also improve geotechnical performance of the roof-support system where an automation system can ensure that shields are set consistently.

Automatic horizon control can more effectively steer the longwall in the seam to minimize product dilution and can also contribute to more-effective strata control by accurately leaving coal on the roof and/or floor to protect weaker strata. In the safety context, automation provides the ability for the mine to remove people from hazardous areas, minimizing exposure to dust, heat, noise, and danger from roof and face falls.

Automatic Face Alignment and Creep Control

Automated face alignment is now a mature technology, and all longwall roof support manufacturers offer systems that deliver effective face alignment automation solutions. These systems allow desired face profiles to be entered into shield-control systems through appropriate graphical user interfaces, and shield-control systems are capable of moving individual shields by calculated distances and are thus also able to coordinate the motion of assemblies of shields to achieve desired profiles along the entire face. Shield hydraulic control systems have been enhanced to allow accurate control of double-acting (D/A) ram motion, and sensors to reliably measure D/A ram travel have been incorporated into shield designs.

Until recently, the major defect in automatic face alignment has been the inability to automatically and reliably measure the actual geometry of the longwall. True closed-loop control of face alignment can only be achieved by comparing the physically measured location of the face with the target location and then minimizing the resultant error. Previous methods were largely based on measuring the accumulated motion of shield D/A rams to indicate face geometry, which gave only an approximate solution with increasing accumulation errors. This situation has been remedied recently through the development of the LASC (Longwall Automation Steering Committee) technology, which measures three-dimensional shearer position directly through an inertial navigation-based SPMS (shearer position measurement system). Because the shearer actually cuts the face, direct measurement of shearer position is the best indicator of face geometry. Open specifications for SPMS data outputs have been devised enabling LASC technology to be applied to any combination of face equipment. The reader is referred to www.lascautomation.com for details of LASC specifications and more-detailed LASC technology descriptions. All face equipment manufacturers now offer LASC technology to the market.

Sensors that measure the position of longwall face equipment relative to the gate-road ribs can be used to provide a measure of automatic creep control. If motion of gate-end equipment relative to the ribs is detected, appropriate lead or lag of the face can be introduced into the basic face geometry input to the automation system. Although LASC laser-based creep sensors are now available to provide this measurement, transformation of this information directly into tailgate lead or lag values is highly site dependent and requires operator input.

Face Alignment Control System Example

Contemporary graphical user interfaces (GUIs) for longwall roof support control systems can be used to display the state of sections of a complete longwall face that can exceed 200 shields in current operations. They can also display the leg hydraulic pressures. This display gives immediate information regarding the hydraulic performance of the supports and can also show through color change when particular shields are not set correctly or are being excessively loaded by the roof strata.

When the face has become misaligned with respect to the target face line, it is seen as an uncut wedge developing between the desired profile of the unmined coal and the AFC. To realign the face, a wedge cut must be executed in the current shearer run to realign the supports perpendicular to the longwall block. This is achieved by making proportional changes in the shield advance distances programmed to introduce a compensating wedge shape in the face, eliminating the misalignment as the shields advance after the shearer passes. The success of this kind of control depends on accurate measurement of face profile and D/A ram extension as outlined in this chapter.

It is difficult to accurately quantify productivity benefits due to contribution from specific automation system elements. However, in the case of LASC-based face alignment, sustained productivity improvement of 130 t/h was reported (Reid 2008). Other productivity improvement information is company-confidential to individual equipment suppliers.

Automated Horizon Control

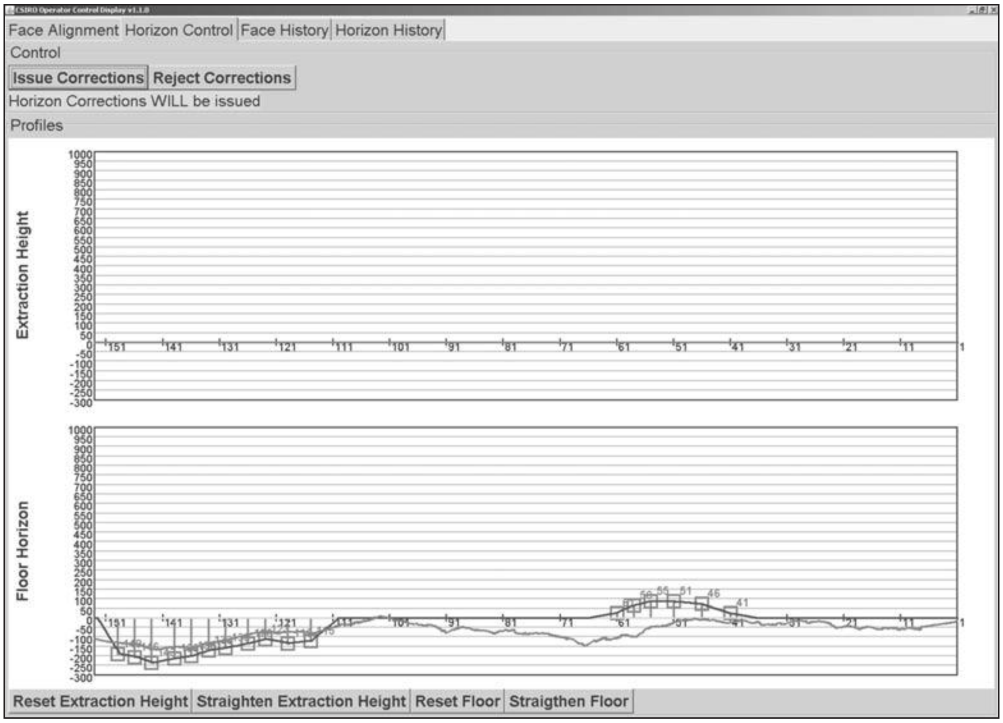
Longwall horizon control—manual or automated—is a challenging task. Whereas the overall goal of horizon control is to ensure that as far as possible only coal is extracted, there are a multitude of site-specific considerations that detract from a mine's ability to achieve that goal. It might not be possible to detect seam boundaries effectively in order to prevent the shearer drums from cutting surrounding rock. In the case of thick seams where visible or other cues to indicate seam trajectory are absent, it is difficult to steer on a consistent path between the gate roads. In other cases, seam undulations along the face or into the panel might mean that equipment cannot articulate sufficiently to track the actual horizons, and roof or floor is cut as a consequence. Problems in detecting fault conditions ahead of mining could mean it is necessary to mine through the faulted zone at short notice.

Automation of horizon control is in the developing stages. The most successful strategy so far has been based on training an automation system using a human operator employing traditional manual cues for horizon detection and control to steer the shearer. The learned extraction process is then repeated automatically until some departure from the horizon-control strategy is observed, such as roof or floor being cut. The training process is then repeated. The advantage of this process is that operator exposure to face conditions is at least reduced. The accuracy of this process has been improved by the availability of the LASC technology, which gives high-accuracy floor-horizon measurements. All shearer manufacturers offer systems that are variations on this basic strategy.

The next stage in the process is to use sensors that can replace the horizon-sensing capability of human operators, or bring to bear new horizon-sensing results. Coal interface detection (CID) sensors based on natural gamma emission by surrounding strata, thermal infrared detection, ground-penetrating radar, optical marker band tracking, and other methods have been developed with varying results. The only commercial CID sensors currently available are based on natural gamma radiation and detection of electromagnetic propagation differences between coal and surrounding strata; several of the other methods are still in the research stage.

Figure 9.8-2 shows a GUI for an interactive automated horizon control system based on the LASC technology. The GUI accepts and displays horizon information over the full face length. The upper screen enables an operator to enter adjustments to a nominal extraction-height setting that has been independently set in the shearer control system. The flat line shows that no operator adjustments have been selected.

The lower screen enables the operator to view recommended floor profiles and to input adjustments manually. The system then automatically generates LASC-recommended floor-height adjustment for the next complete shearer run. In its simplest form, this adjustment is generated by extrapolating the average floor profile from the previous five shears. At this stage of development of automated horizon control, the operator is in the loop. The operator has the ability to input manual floor-height adjustment on a per-shield basis.



Courtesy of CSIRO Division of Earth Science and Resource Engineering.

Figure 9.8-2 A prototype automated horizon control system user interface

The operator's task is to input manual horizon inputs to match the recommended profile as closely as possible. The operator is also able to take into account off-system inputs such as physical observations along the face or known conditions that would preclude the shearer being able to execute the automation system's recommended track. Close matching of manual to automatic settings is shown on the left-hand side of the display in Figure 9.8-2. On the right-hand side, the operator has chosen a floor profile that does not closely follow the predicted floor alignment.

Figure 9.8-2 shows the smooth profile that the automation system generates compared to the manual inputs. This profile then becomes the floor-height adjustment target for the OEM's shearer-control system.

"State-Based" Shearer Automation

In recent years, one of the most successful initiatives has been the development of programmed shearer automation on a logical state basis. The concept is similar to the training method of horizon control described earlier. The operating parameters required for the shearer to completely execute a single pass of a particular cutting sequence are defined as a series of logical states that encompass combinations of ranging arm positions, haulage speeds, and various sensor outputs including motor currents, position measurements, and so on. As the shearer travels along the face, it sequences through the previously defined states. If no anomalous states are encountered, the pass will be executed successfully and the machine will commence the next pass. Error states can be defined to handle operational exceptions, but some errors will cause the system to halt when human intervention is required. When this system was first introduced, significant productivity improvements resulted immediately. This was attributed largely to the consistency that was possible when operation was based on a fixed programmed sequence and not subject to variable operator inputs.

Challenges to Overcome

The automation technologies described in this chapter are able to successfully automate the routine operations of a longwall. The major problems encountered in longwall automation are concerned primarily with the management of exceptions to normal operations caused by the fact that an underground mine is actually not a factory environment and is subject to the vagaries of nature. To achieve full automation and the "workerless face," many more sensors need to be developed to replace the observing roles carried out by face operators at present. Additionally, there are issues with ensuring that equipment operates to the standards required for automation in a harsh, hazardous environment.

Mine Requirements for Longwall Automation

The face alignment and programmed shearer automation systems can be implemented in most mines. In the case of horizon control, it is necessary to establish whether local seam conditions exist that allow horizon sensors to be effective. Equipment manufacturers can offer advice as to which sensors will be appropriate.

For modern automation systems, high-quality data communications links to sensors and face equipment are required. Longwall manufacturers now provide Ethernet connectivity on face equipment as a matter of course. For these systems to be effective at a mine, corresponding communications infrastructure must be available between the face, the surface, and wider into the mining company's and its service providers' data communication networks.

Optimal longwall automation results can be achieved only if all elements in the mining process are operating reliably and at peak performance. Automation systems require particular attention to engineering and maintenance standards at the mine to ensure that all components of the system are effective. An automation culture must be developed and maintained in the work force so that automated operation is fundamental to production.

Dragline Automation

The rate of overburden removal is almost always the bottleneck in open-cut coal mining, and draglines (the most cost-effective means of overburden removal) are the tools of choice. To address this production bottleneck, various strategies have been adopted. First, manufacturers have increased in size and power over the past 40 years, but there appears to be a physical limit in just how large these machines can become before they are impractical. Second, mines have put substantial effort into operator training and production monitoring while also routinely overloading the machines. These strategies are unable to yield further improvement, but continually increasing stripping ratios (which have increased from 2–5:1 to 8–15:1 today) mean that the need is still acute.

Automation is therefore increasingly seen as the next phase in the evolution of the dragline and the industry's quest for increased production. In addition, many in the industry believe that automation can also offer the possibility of lower maintenance costs through the control of the machine within its design limits (a task that human operators often struggle with). Finally, automation systems can deliver consistency and an equivalent skill level that can result in a system that overall will outperform human operators—it may not be as fast as the best operator at the beginning of a shift, but because of its consistent operation, it will on average outperform the pool of human operators. Automation further promises a means of overcoming this skill shortage and would seem inevitable in the mining industry.

Automation Development

The history of dragline automation can be traced back to the late 1980s when BHP Billiton performed a series of trials at a mine in central Queensland, Australia (Allison 1992). These trials attempted to show that a dragline could be partially automated by replaying the control signals of an experienced operator. However, one of the conclusions of these trials was that the instantaneous swing angle of the bucket beneath the boom must be taken into account, making the simple replay strategy infeasible; that is, there must be some kind of bucket swing feedback into the control system. In 1993, CSIRO researchers funded by the mining industry began to investigate bucket-swing sensing and the subsequent automatic control of a dragline's swing motion. Initial experiments determined that vision systems, touted at the time as the solution to the bucket swing-angle sensing issue, could not operate around the clock in the adverse weather and visibility conditions typically experienced at mines. Instead, these camera-based prototypes were replaced by two-dimensional (2-D) scanning laser range finders, which became commercially available in 1995. These sensors proved to be very robust and adaptable to the weather and lighting conditions as well as the mechanically harsh environment experienced at the end of a dragline boom where they were mounted. With such a system it became possible to accurately measure the swing angle of the hoist ropes and hence the angle the bucket-rope plane made with the vertical boom plane (Roberts et al. 1999).

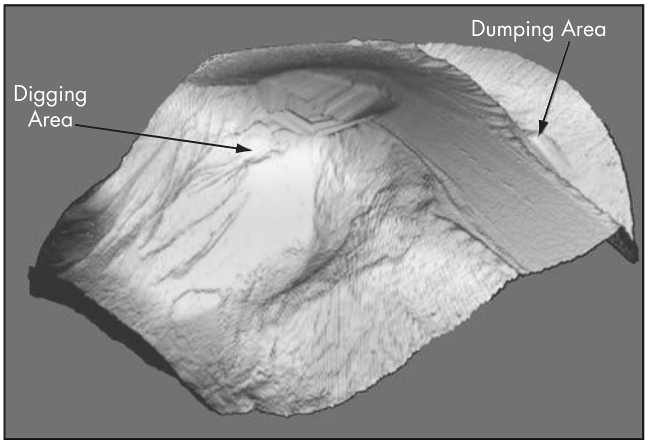
Automation of BE1370 Dragline Demonstration

A full-scale proof-of-concept automated swing-control system was developed on a BE1370 dragline at the Tarong coal mine in South East Queensland, Australia. It performed a fully automatic dig-to-dump-to-dig motion, whereas bucket filling remained the responsibility of the operator. A key component of the system was active controls—the joysticks and pedals were driven by small motors to affect computer control of the dragline, but the operator could override at any time and regain control by moving one of the joysticks. This system was further developed on a BE1350 at the Boundary Hill pit in central Queensland, where in 2002 a 2-week production trial was undertaken (Corke et al. 2003). In total, 12,235 cycles were performed, 3,042 using the automation system and 9,193 fully manually. More than 250,000 t of material were moved autonomously during this trial. In summary, three significant conclusions were reached. First, the system performed more than half of its cycles in better time than the average of the operators working over that period. Experienced operators observing the dragline could not tell a manual cycle from an automatic one. Second, the performance of the automation system was compromised by the system's lack of accurate terrain information. The system relied on the operators marking the position of the spoil piles, highwall, and any other obstacles. This was done by placing the bucket over these locations and pressing a button on the joystick controller. However, a safety margin was introduced to ensure that the bucket never collided with the terrain, and this typically added a 5%–10% time penalty to each automated cycle (due to overhoisting). Third, it was clear that the automation system treated the dragline more gently than the human operators. No specific maintenance benefits could be derived from such a short trial, but the time history of control outputs from the automation system were far smoother than the human operators.

The same CSIRO team between 2002 and 2006 addressed the lack of real-time situational awareness around the dragline where they developed a digital terrain mapping (DTM) system. As well as allowing an automation system with a smaller safety margin, the accurate knowledge of terrain can be used by the automation system to plan optimal bucket trajectories. The successful use of 2-D laser scanning systems for rope location (Roberts et al. 1999) inspired the CSIRO researchers to trial a longer-range scanner on the boom tip, giving it a view of the terrain immediately beneath the boom. With this arrangement, all the terrain around the dragline could be mapped as the machine rotated (Roberts et al. 2003). Initial standalone trials (without the automated swing control) proved the concept, and a 4-week production trial was undertaken in 2006 on the Boundary Hill BE1350. A DTM produced during this trial is shown in Figure 9.8-3. This trial showed that DTMs could be produced routinely in a production environment and that the DTMs themselves were useful to the mine planners and surveyors, even without an automated dragline control system. Further, a level of detail never envisaged was obtained in that the material movement of every cycle could be recorded if desired.

Automated Dragline Digging and Precision Dumping

In 2005, the CSIRO team demonstrated a fully autonomous tenth-scale model dragline that incorporated bucket-swing



Courtesy of CSIRO.

Figure 9.8-3 Digital terrain map produced during a 4-week production trial

feedback, generation of DTMs, optimal bucket-path planning, and autonomous digging (Dunbabin et al. 2006).

The practice of precision dumping has again been raised now that autonomous draglines have been shown to be feasible. The concept of a dragline being capable of accurately dumping its load into a hopper and feeding into a conveyor or into trucks could transform certain mining operations. The CSIRO team has shown how the tenth-scale model dragline can reliably dump material directly into a truck tray (scaled accordingly).

Current Status

The past 15 years have seen a number of proof-of-concepts and demonstrations in full production environments with trials lasting multiple weeks (Winstanley et al. 2007). Dragline automation is now technically possible; economics and the market will determine when it is finally introduced.

FUTURE CHALLENGES

A major challenge over the next decade is to automate the unit operations themselves, understanding that some of the equipment in a group may remain under direct human control or be semiautomated. Thus, each automated machine must be able to operate interdependently with the other machinery associated with the unit operation. The absence of this capability currently is a major barrier to the deployment of automation technologies in mining. Understanding how to achieve safe, interdependent operation in mixed fleets is the most important and significant technical barrier to the further development of mining automation technologies.

McAree and Lever (2003) provide recommendations for where investments in surface mining automation research will provide the short-to-medium-term benefits to the mining industry while making progress toward full automation. They are as follows:

- **Advanced sensing technologies for the mine environment.** This includes the processing of sensor data to extract information and sensor fusion for combining data from several sensor sources. Imaging technologies for terrain and local-area mapping are important, as current technologies are sensitive to dust, vibration, and temperature variations.
- **Use of mine-wide information systems to facilitate unit interactions.** Mine-wide information systems play a critical role in controlling the interactions of automated equipment. This task will be complicated significantly if common communications protocol is not adopted that would allow complete interoperability between sensors and mine information software from different vendors.
- **Extended use of existing and new sensors aboard equipment.** Data from onboard sensors can be used not only to monitor and report equipment status and performance, but to develop detailed understanding of equipment operations and their interaction with mining processes. Understanding these operations is an important step for successful automation.
- **Developing duty meters to manage the trade-offs between equipment productivity and damage, and to predict failures.** Automation systems must perform the many maintenance, fault detection, and isolation functions that operators currently execute. It is important to understand how machine performance and duty trade against each other to optimize the productivity of automated equipment. Poor availability poses the same problem for automated equipment as it does for manually operated equipment.

The widespread acceptance of automation and robotics technologies in mining over the coming decades will depend on a number of factors, including

- Simple and effective integration with mining processes;
- Changes to existing mining processes to simplify the use of automation;
- Management acceptance to ensure automation is seen as a benefit, not a threat, to the mining work force;
- Implementation occurring in stages starting with narrow domain or task requirements and then increasing capability and complexity (machines then systems);
- Meeting mine requirements of productivity, cost, and flexibility;
- Balancing technical complexity with robustness;
- Transparent operation wherein mine personnel must clearly understand the capabilities and limitations of the systems; and
- Turnkey systems, as much as possible.

A major threat to the uptake of mining automation is the desire for a quick success, which leads to shortcuts in technology development and poor implementations.

A VIEW OF AUTOMATION AND THE MINE OF THE FUTURE

For decades, visionaries have predicted that autonomous machines would be critical to the future of mining. The major drivers have been safety, the need to work in remote locations, the lack of operators in general, long-term reliability improvement, and efficiency gains. These visions are rapidly becoming a reality.

Safety Advantages

One of the most often-cited reasons for autonomous mining is safety. Although the fatality rate published by the Mine Safety and Health Administration (MSHA 2009) shows a reduction in fatalities, significant improvement is still needed. Despite tremendous effort on the part of regulatory agencies, mining companies, and equipment suppliers, the total number of fatalities in the United States has on average not improved substantially since 2003. Similar statistics from Australia, South America, and China show that further safety improvements are very challenging to achieve and potentially even harder to maintain. One clear strategy to reduce injuries and to easily maintain the reductions in injuries is to remove people from harm's way. For example, it is estimated that automation and ROCs offer the opportunity to remove up to 80% of haulage-system operators from surface mines. Fewer people involved in mining operations translates to fewer opportunities for safety-related incidents and fewer opportunities for long-term disabilities caused by repetitive operations.

Integrated Site Awareness

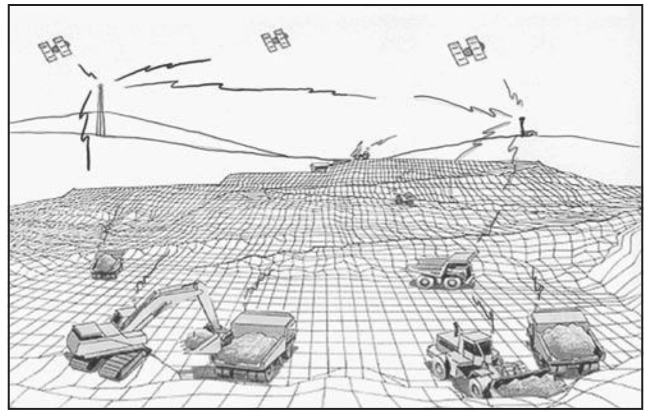
Another significant safety advantage provided by autonomous systems can be achieved through integrated site awareness or situational awareness. Probably the most easily understood example of situational awareness is the accident prevention provided by air traffic controls. By tracking most planes and controlling corridors, the situational awareness provided by air traffic controls helps reduce mid-air collisions. Studies indicate that situational awareness can lead to substantially improved performance in complex military environments (Endsley 1995). Although managing a mine or operating mining equipment may not be as complex as operating a military aircraft or as demanding as managing a battlefield, the continual, around-the-clock nature of the mine operation makes site awareness just as critical (Figure 9.8-4). A well-integrated mine of the near future will allow all machines and potentially mobile objects to be tracked in real time. Integrated site awareness will allow both automated and human machines to easily perceive and comprehend the current situation, which should lead to better decisions and a safer environment for both.

No Fatigue and Minimized Opportunity for Operator Error

Although recent estimates of the effect of fatigue in accidents vary considerably (from 2% to 41% according to De Gennaro et al. 2001), fatigue is clearly recognized as a significant contributor to mine accidents. Furthermore, operator error caused by all sources (including fatigue) may account for as much as 88% of all accidents (Heinrich et al. 1980). It is commonly recognized that the best means to avoid accidents is to design out the opportunity for the accident. Using automated systems significantly reduces the opportunity for errors and provides a means to accurately track, correct, and control any remaining issues. Automated systems never get tired, bored, distracted, or inattentive. There will certainly be challenges related to performance in all environmental conditions, but these should be well understood and will improve over time.

Remote Locations

It is anticipated that many new mines will be located in regions with low population densities. The cost to develop housing, schools, hospitals, and other required infrastructure can significantly impact the ability for a given site to be a cost leader (have a production cost below the average cost in the industry). Many remote sites are supported by a large number of fly-in/fly-out (FIFO) employees, which can lead to "FIFO fatigue" and potential higher turnover rates (due to the variability in mining, it is difficult to make accurate assessments).



Courtesy of Caterpillar, Inc.

Figure 9.8-4 Communication infrastructure for a future mine

Informal feedback from the mining industry suggests that it costs mine sites 100% of an annual salary to replace a worker and a further 50% to train the replacement to a desired productive level (Rowland Communication Group 2004). The cost to attract workers and the worker turnover at remote locations can severely impact the operating cost, production, and safety at these remote mine-site locations. Reducing the total number of workers via automation and allowing more of the remaining workers to work at ROCs could significantly reduce FIFO fatigue and may reduce employee turnover.

Availability of Operators

Scarcity of skilled operators during boom times is often cited as a major problem for mining expansion (Barta 2005). Certainly mines that follow the volatility exploitation model (essentially, mines that are only operated during times of high commodity prices) will make it difficult for the industry to maintain a stable, highly trained work force. Using autonomous systems could minimize the volatility and reduce the start-up and shutdown times of higher-cost operations.

Efficiency

Another key reason for interest in automation is the expected gains in overall relative efficiency, where relative efficiency is defined as tons moved per day relative to a nonautomated mine with the same contingent of machines. Several factors can dramatically influence the efficiency gains at any particular site including load size, cycle time (speed, queuing time, spotting time, loading time, and dumping time), accuracy (percentage of loads delivered to the right location), machine availability, and operator availability (discounted for training time, breaks, absence, etc.). For haulage systems, these can be written as

- Relative productivity = (relative load × relative accuracy × relative machine availability × relative operator availability) / relative cycle time
- Relative load = (autonomous machine load) / (manual machine load). Expect this ratio to equal 100%.
- Relative accuracy. This is the percentage of total loads (waste and ore) that are dumped in the correct location. The relative accuracy should improve slightly for automated machines.

- Relative machine availability (the percentage of time that the machine is down due to a mechanical or electrical failure). It is assumed that machine availability will improve over time with automation, due to the more-consistent machine operation.
- Relative operator availability. Operator availability can vary widely depending largely on the local mining process. This is an area of substantial potential gain for autonomous systems. For example, if an existing mine with no automation achieves 16 h/d of actual working time and the same mine with an automated haulage system can achieve 22 h/d of operation, it is a 38% increase.
- Relative cycle time. This is the average total time per cycle with an autonomous system divided by the average total time per cycle without an autonomous system. Relative cycle time includes the loading time, transporting time, dump time, and queuing time. For underground mining systems that are already using remotely controlled machines, automation should provide a significant improvement in cycle time. But for haulage systems that are currently using manned machines, the relative cycle time may be lower for initial automated systems. However, due to the expected rapid evolution of autonomous systems, it is anticipated that future generations will match the cycle times of well-controlled mines that operate machines within their design limits. In other words, the machines will be operated according to their design limits and the mine rules.

Efficiency Gains Though Process Control

Arguably, the greatest potential improvement may be in process control. The availability of machines that operate consistently and as instructed provides the opportunity for mine operators to fine-tune their operations. Future mine systems will allow every machine, person, and process to be accurately tracked. This will provide unique capabilities to accurately model all mine processes using real-time models to improve mine-planning capabilities. The autonomous machine will be the most salient change, but the real driving force for improvement will be the consistent, predictable process coordinated by an information-rich environment.

An example of a related industry is that of grade-control systems used in construction. These have shown process control–related improvements of 30%–50% and associated fuel and carbon dioxide reductions of 43% (Caterpillar 2006a). Process control is expected to be a strong area of dramatic innovation as autonomous machines begin to be deployed. Although independent data is not available, a recent article regarding the deployment of Caterpillar's MineGem technology at the Jundee gold mine in Western Australia states that "MineGem cut down on wear and tear on the machines." According to Gary Mills, Jundee's mining manager,

> What was happening previously too is that the boggers were bouncing off the walls and causing a lot of damage.…The laser-driven boggers stay off the walls, so you don't get any damage even though they can go faster.…The need for secondary stockpiles in the mine has also been removed by the faster tramming speeds, cutting down that cost as well (Haycock 2009).

Challenges and Changes Required for Successful Automated Systems

Clearly, putting an autonomous machine into an otherwise unchanged mine will not provide the expected gains. For example, in general, autonomous trucks will initially travel at slower speeds than human-operated trucks, causing significant loss of efficiency for the human-operated trucks.

Information System Improvements

One of the biggest changes will be the amount of information needed to run a mine smoothly. An autonomous mine will be very much information driven including everything from the detailed mine model to product levels, payloads, and the location of every asset. This will drive several requirements on communications and information infrastructure:

- High-bandwidth communications with quality of service capability will be a requirement. It is strongly suggested to have dedicated communications channels to avoid issues with lost or late communications.
- Tracking and communicating the location of every asset will be a key layer of the obstacle-avoidance strategy. Neither people nor machines should be allowed to operate within an autonomy zone without proper electronic tagging.
- Every asset will need to provide vital information such as its position, heading, health, status, destination, detected objects, and potential road (map) changes. In addition, it would be useful to communicate any potential changes about the road surface (wet, rough surface, soft, etc.).
- This information will be in addition to the existing productivity and maintenance information that is used for typical mine management.

Accurate Mine and Machine Model

Maintaining an up-to-date mine model will be absolutely critical to autonomous machines. Although machines should have secondary sensors to detect inconsistencies in the mine model, autonomous machines will by necessity assume that the mine model is correct. Most machines should be programmed to halt if they detect inconsistencies in the mine model. Analysis of the inconsistencies and self-correction would be the next phase of development for automated systems. The definition of the mine model will require orders of magnitude more detailed than existing mine models that are used for automated assignments or dispatching.

All mining machines will have to be modeled as well. The fidelity of the machine model will be dependent on the class of machine such as autonomous machines, interactive machines (such as loading machines), support machines, and mobile platforms (light plants, pumps, etc.). Autonomous machines, including both kinematic and dynamic models, will need to be very accurately modeled. Interactive machines (such as loaders) will need to have a very accurate kinematic model and accurate positioning. Support machines may be modeled much more simply, and mobile platforms may be modeled simply as an exclusion zone. Any significant changes to these machines will need to be tracked and modeled (e.g., a pickup pulling a trailer suddenly appears to have grown in length).

Required Operational Changes

Successful installation of an autonomous system will require operational changes in several key areas:

- **Working environment.** Obtaining consistent predictable productivity will require a reasonably predictable working environment. Anything that alters the working environment such as water trucks will need to be accurately controlled and monitored.
- **Improved information system maintenance.** Maintaining the electronic infrastructure will include positioning systems and dedicated high-bandwidth communications systems. In general, automated systems will require either a dedicated network or a redundant network with quality of service assurance. In addition, a backup network should be installed for emergency and autonomy stop functions.
- **Avoiding mixed fleets.** In general, autonomous machines will travel at different speeds than human-operated machines (faster in some cases and slower in others), and mixing manned and unmanned machines may cause significant loss of efficiency for the human-operated trucks. Automated equipment may be programmed to be more "sensitive" to human-operated machines, potentially slowing down to avoid any risk of an accident, and will, therefore, tend to be less efficient.

Machine Health and Maintenance

Site-level machine-health monitoring will become more critical as autonomous machines become more prevalent. In addition, there are still items that are only detectable by human operators (some vibrations, noises, etc.). Development of new prognostics and diagnostics will be required, and maintenance procedures will become much more critical.

CASE STUDY: AUTOMATED SURFACE BLASTHOLE DRILLING AT THE WEST ANGELAS IRON ORE MINE

This section provides an overview of blasthole drilling automation and uses the data associated with the implementation of this application at Rio Tinto's West Angelas iron ore mine.

An automated surface drill is generally considered one that can tram, level, and drill automatically. Automated blasthole drilling is considered easier to adopt into an existing mine fleet than other large, automated mobile equipment due to its relatively slow movement and generally isolated operation.

The automation of surface blasthole drilling has made significant advances into the mining industry since 2005. Some of the cited benefits are

- Repeatability of drilling process
- Lower total cost per meter
- Increased production per drill
- Longer use of assets
- Lower labor needs
- Better hole stability
- Better predictability of blast fragmentation

Issues with Implementation

During the implementation of a new automated drill system, there can be an expectation that the system will perform at a level at least comparable to the existing system. If the system is not performing within expectation, the technology may not be adopted.

Table 9.8-1 Basic sensors for an automated drill

Description	Typical Sensors Used
Drill-rig position	High-precision Global Positioning Systems, ground-based satellites, inertial measurement units, lasers
Drill-hole depth	Lasers, string encoders, wheel encoders, magnetic pulse
Drill-rotation velocity	Magnetic pickup on drill-drive gearbox, flowmeter on rotation hydraulic circuit
Drill-rig roll and pitch	Tiltmeters
Track speed	Track encoders

Source: McHugh 2009.

To plan for implementation success, mine operators should consider the following elements:

- **Drill automation approach.** If the drill automation approach is different from the current manual drilling approach, this must be clearly explained to the stakeholders. Some degree of customization of the automation to suit the ground conditions should occur before the drill is used in full production.
- **Automation sensors.** The automation system critical sensors must be accurate and able to survive in a mining environment. Sensors that detect the surrounding environment (e.g., vision systems) must be of sufficient resolution to determine changing conditions such as collapsed faces or large boulders to prevent catastrophic damage to the machine. Typical sensors required to automate a large blasthole drill are displayed in Table 9.8-1.
- **Communication infrastructure.** If the drill is to be remotely supervised, the communication system selected must be suitable for the application. This will require site surveys and consideration of future requirements.
- **Service support and training.** A sustainable production system requires service support and training. The model of service and support must be clearly defined before implementation.
- **Other dependent mine processes.** The drill automation will affect other processes such as normal drill servicing, sampling, and charging due to more restricted access to the drill area. New procedures will be required before implementation.
- **Safety.** Mine operators may choose soft procedural safety controls rather than more expensive engineering controls that are difficult to maintain in a rapidly changing mine environment. The automation of blasthole drilling may not require interaction with other mine equipment, thus reducing system complexity. The use of remotely operated automated machines provides a much safer environment for drill operators, removing the operator from potentially hazardous areas such as unstable pit walls, unstable pit floors, hazardous airborne dust, and hazardous noise.

  The use of an independent emergency shutdown system that can stop the engine as fast as practicable would provide a level of redundancy in the case of uncontrolled movement. This is very important if a remote operator is supervising the automated drill or drills.

Table 9.8-2 Comparison of drill accuracy for automated and manual operation

Accuracy	Manual	Manual with High-Precision GPS Guidance	Automated
Drill-collar position average error against design, m	0.563	0.259	0.144
Drill-collar depth average error against design, m	0.51	0.33	0.05

Source: McHugh 2009.

Table 9.8-3 Comparison of drill productivity under automated and manual operation

Productivity	Manual	Manual with High-Precision GPS Guidance	Automated
Tramming time median, s	75	43	58
Leveling time mean, s	35	28	40

Source: McHugh 2009.

Table 9.8-4 Comparison of overall drill productivity for automated and manual operation

Productivity	Drill 3 Auto	Drill 3 Manual	Drill 3 Total	Drill 4 Total	Drill 5 Total	Drill 11 Total	Drill 12 Total	Drill 104 Total
Total drill length, m	36,728	3,599	40,326	44,365	25,551	38,398	40,220	38,485
Total drill time, h	576	55	631	675	506	651	815	708
Penetration rate, m/h	64	65	64	66	50	59	49	54
Availability, %			91	89	76	89	93	94
Use, %			51	55	44	55	65	56

Source: McHugh 2009.

Automation Capability

The automation of the large-surface blasthole rigs has advanced at a faster rate than the smaller articulated boom rigs. Larger rigs are considered easier to automate as they have fewer degrees of mast movement. They are generally located in mines with large, simpler patterns with generally vertical rotary holes. The benches are generally well maintained and provide the ideal environment for navigation and leveling. Automation of rotary drilling is considered easier than hammer drilling. Hammer drilling requires a precise rotation speed that must adapt according to the penetration rate. Rotary drilling, on the other hand, will generally have a fixed rotation speed that does not vary as much with the geology.

Mine operators will always encounter different drilling environments, and the more accepted automated drill systems are the ones that allow intervention either manually or remotely to deal with exceptions. This feature is important as it generally allows little loss in production over completely manual systems, aiding in system acceptance.

The automation of some ancillary functions of the drilling process will require significant engineering changes to occur such as bit changing and mode of drilling. Since these processes use consumables of the drill that wear quickly, in the near term they are probably better handled in a semiautomated mode.

To make the drill ready for automation it is generally considered that the drill must be set up for electronic control. Many of the new surface drills use the controller-area network bus that was developed for the automotive industry.

Advantages of Drill Automation

Automation of surface blasthole drill rigs has demonstrated greater accuracy and repeatability with similar rates of productivity compared to manual operation. Remote supervision of automated drills has allowed one operator to control more than one drill.

Field trials of a proprietary automated system on an 80-t Terex SKSS16 rotary and percussion blasthole drill at the West Angelas iron ore mine demonstrated significant improvements in accuracy over manual operation. The summary of the results are displayed in Tables 9.8-2 and 9.8-3.

Table 9.8-4 compares the same automated drill performance against five other same-model drills operated at the mine in manual mode over a period of 9 weeks. The remotely supervised drill was able to drill more than 90% of all holes in automation mode.

The high degree of repeatability of the automated drilling process allows mine operators to choose a drilling approach that best suits their operation with a high degree of confidence that the drill will achieve it. The selected drill approach should ultimately help achieve the overall mine strategy. The repeatability also helps mine operators to better understand the trade-offs in different approaches. The mine geology can have a significant impact on which approach is required at different areas of the mine, and therefore it is unlikely that one single approach will be optimal in achieving the mine strategy. Approaches may include

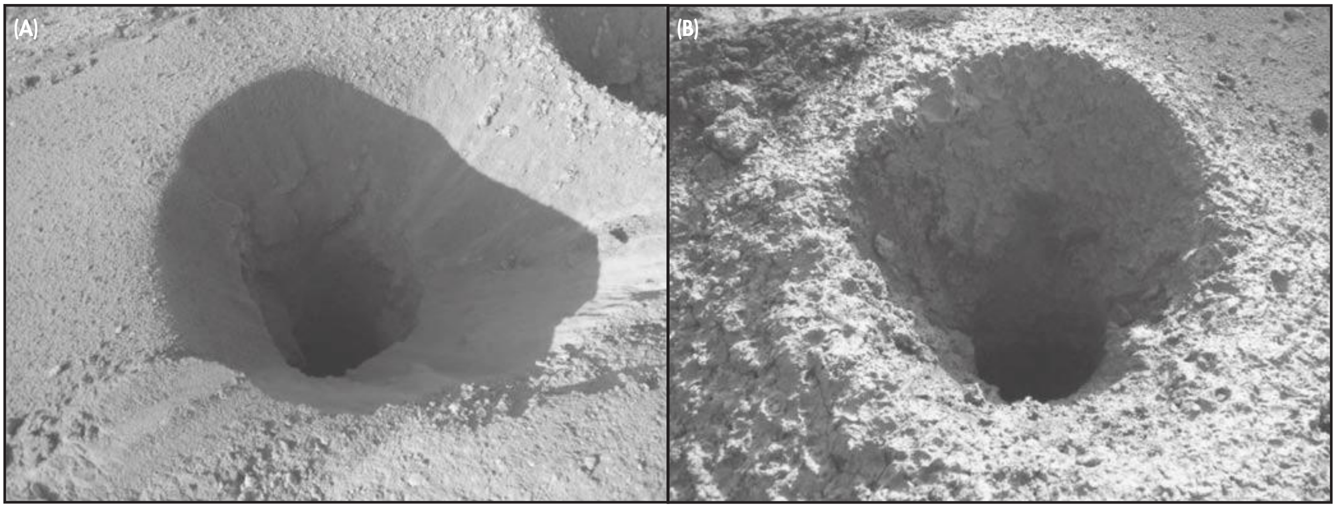
- Trading off production performance for improved drill bit wear rates,
- Drilling the straightest hole,
- Maintaining hole stability to prevent redrilling, and
- Lowering overall stress and vibration on the drill mast and chassis.

In a manual drilling operation, expert drillers are those who can best follow the approach selected by management and adjust the strategy according to the changing geology and condition of the drill. The automation of these approaches will generally reduce the time required to train a new operator to perform like an expert driller. Figure 9.8-5 is a comparison of a manually drilled hole and an automated hole drilled 5 m apart in the same geology. The automated drill shows the correct amount of water injection to maintain a stable collar in that geology.

Disadvantages of Drill Automation

Although the advantages of automation are significant, there remain some disadvantages:

- The automated drill is best-suited to stable geology.



Source: McHugh 2009.

Figure 9.8-5 Comparison of drill collars between (A) manual and (B) automated drill holes

- It can be slower than certain parts of the drill cycle as it maintains the level of accuracy required.
- Sensor failure on the drill is common and could stop the whole system.
- Without significant sensors and processing, the drill may not detect the changing drilling environment such as
  - Collapsing collars,
  - Collapsing holes,
  - Collapsed bench edges,
  - Obstacles such as rocks fallen on the bench, and
  - Potential interaction with other equipment such as explosive-charging carriers.
- Detection of worn bits or drill-string failure can be difficult.
- High-precision GPS may be difficult in deep pits and may require ground-based satellite augmentation.

Challenges to Overcome

To improve the function and reliability of automated systems, several factors need to be addressed:

- Provision for reliable sensors capable of withstanding extreme conditions experienced on the drill
- If operating remotely, reliable wireless communication with significant bandwidth
- The use of prior geological knowledge to adjust the automated settings
- Adequate vision coverage to supervise the rig remotely
- Complex movement path planning between rows
- Integration with other mine equipment such as explosives trucks

Advances and Productivity

Wireless communication for supervision of automated drills enables the use of other real-time sensors for purposes such as rock recognition, automated sampling, and downhole sensors. Prior knowledge of the rock behavior could be incorporated into the automated function design.

The use of remotely supervised automated drills enables the operation of at least two drills at once. As automation becomes more reliable and remotely supervised, it should be possible to run more than three units with one operator.

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