New Technology & Innovation

Report 2 – Autonomous Mining Equipment

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Executive Summary

Innovation and New Technology

This is the second report by RFC Ambrian in our series of reports on innovation and new technology in the mining industry. In the first report we touched on some of the concepts and issues being discussed around the implementation of new technology, including 'the fourth industrial revolution' and 'Mining 4.0'. We also took a look at some of the strategies being implemented by some of the larger mining companies and tried to assess the levels of progress and success.

In this report we examine one of the most highlighted areas of new technology and innovation in the mining sector, the development of autonomous mining equipment. This has reached an important level of maturity, although it is still evolving and its penetration across the industry is still in its infancy. This includes both surface and underground equipment, but most notably for surface mine haulage trucks where it has been an area of significant focus for major mining companies.

Autonomous Haulage Systems

The Autonomous Haulage Systems (AHS) have evolved from improvements in GPS for positioning and navigation, developments in sensors and detection – particularly radar and LiDAR, improved computing power and on-board monitoring, faster and more reliable networks and internet connection, and the development of effective and accurate algorithms and software. AHS has appeared first at large mine operations where the benefits have the largest impacts, due to the high component of fixed costs in an AHS operation, and in developed countries where there is a shortage of skilled workers and labour costs are higher.

Outlining the potential benefits of AHS is straightforward but finding hard data to support it is more difficult. Companies have made suggestions about the scale of improvement, but they are light on detail, definitions are not clear, and the data varies between companies. Suggested improvements in productivity have come from Caterpillar (15-20%), Fortescue Metals (30%), Komatsu (15%), and Rio Tinto (15%). These improvements are still meaningful, and corporates would argue that every mine is different and that the mining companies and OEMs that have so far implemented AHS have the right to guard this proprietary information and hold on to the competitive advantage.

This report also examines third party reports of calculated benefits achieved using AHS at existing mines and looks at the potential additional benefits that could be achieved from the introduction of AHS in a new surface mine. We also look at the progress of each of the OEMs that are currently involved in AHS and consider some of the practical issues so far reported with AHS and the likely future developments.

Autonomy in Other Surface Equipment

We are also now seeing this same technology used to automate other operations in the surface mine. This includes drill rigs, dozers, loaders and ancillary equipment. Much of this equipment is currently, at best, semi-autonomous, although a few mines have implemented fully autonomous drill rigs and dozers. Moving this equipment to full autonomy offers significant production improvements, although the scale of actual savings is not likely to be as great as those achieved with AHS. However, we have not yet seen quantified the downstream benefits of the resultant improved drilling and blasting.

The automation of earth moving machines provides another step to increased productivity within the mine. However, loaders face additional challenges as a result of the variability of the loading face and the risk of collisions with the haulage trucks. Due to the complex nature of the bucket-media interaction, developing automatic loading functions that are better than or equal to expert manual drivers with regard to performance is a highly difficult task. As a result, fully autonomous loading is not yet commercially available. Some observers suggest that the implementation of fully autonomous surface loading is still some five years away, while others believe that full automation is unlikely.

Underground Mining Equipment

As with surface mining, full autonomy remains the goal of the underground miner. Mining companies and contractors are constantly looking to use technological developments to better utilise their investment in equipment and human resources and improve safety. Particular features of traditional underground mines are: long unproductive periods caused by re-entry times required for operators after blasting; and higher health and safety risks due to geotechnical and environmental challenges. The use of autonomy underground aims to increase the productivity of the equipment and improve the safety of the operators.

Full autonomy in the underground mine is not as advanced as in the surface mine. Haul trucks are used less frequently in underground mines, although a few mines are using haul trucks with AHS. More underground mines perform a short cycle of loading, hauling and dumping from a draw point to a tipping point with LHD equipment. Implementation of autonomous systems underground for LHDs is occurring, however, as with surface loading, one of the major hurdles to automating LHDs is replacing human judgement required for filling the bucket. As a result, fully autonomy is being used for the hauling and dumping cycle, but semi-autonomy is usually used for loading. Successful trials of fully autonomous LHDs have been achieved and Sandvik i-series now offers an automated bucket filling assistant as a standard function. Underground drilling operations are also achieving increased levels of autonomy but are also only semi-autonomous.

Autonomous Rail Haulage Systems

There has been some form of automation on worldwide metro systems for many years, but one area where autonomous technology has yet to gain a foothold is rail freight. Trials are underway in Holland and Germany but implementing autonomous train driving on a complex rail network, with passenger trains and freight trains, is more difficult than on a metro system. The one exception to this is in the mining sector where Rio Tinto has just completed commissioning of the world's first fully autonomous, long distance, heavy-haul rail network which is now in full operation.

Figure 1: Cat Autonomous Haul Truck at Solomon Hub

Source: Fortescue Metals

Slow Pace of Implementation

Despite the acclaimed success and the relative level of maturity of the technology, the wider implementation of AHS does not appear to be happening very fast. The systems of both the two main suppliers (Caterpillar and Komatsu) are well proven and have delivered positive results, although according to consultants both systems also have examples of less-than-expected performance. Nevertheless, the technical issues appear relatively minor and there is interest right across the industry but, in spite of the potentially significant benefits, more mines are not now using AHS.

There are a number of likely reasons for this and one of the most important is a lack of skilled personnel. We believe there is a lack of in-depth knowledge of the technology and limited personnel with the requisite experience, skills, and training throughout the industry's hierarchy. Further, there is a shortage of skilled autonomous operators, developers, and consultants, some of who are moving to the autonomous auto market. Important factors in the success of AHS appear to be the level of management commitment, planning, and focus in the implementation, with the best results reported from well-operated mining sites.

Another factor is likely to be limitations on equipment supply from OEMs for new equipment and truck conversions, either due to manufacturing backlogs or maybe market caution limiting investment. This is allowing the OEMs to be more selective in their customers. However, if the existing suppliers do not develop additional capacity quick enough this could create opportunities for additional entrants in to the market.

Capital availability in the mining industry could also be an issue (although it is less tight than it has been in recent years). Certainly, some lower margin operations might struggle to finance the capital, although the uplift in relative profitability could be transformational, with relatively quick paybacks.

Finally, the historical conservatism of the mining industry is also likely to be a factor. There is still a natural reluctance within the industry to adopt new or unproven technology due to the high capital cost involved and the potential operational and reputational risks involved. This will be compounded if the organisation has limited experience and limited access to the technology.

Automation of Mining Equipment

One of the most highlighted areas of new technology and innovation in the mining sector is the development of autonomous mining equipment. This has reached an important level of maturity, although it is still evolving and its penetration across the industry is still in its infancy. This includes both surface and underground equipment, but most notably for surface mine haulage.

Mines can approach the autonomy of haulage equipment in a number of stages depending on the system offered by the OEM. We have categorised these steps as guided, remote, semi-autonomous, and autonomous.

- Guided is the first stage of automation with the inclusion of some kind of user interface providing guidance. The equipment operators still have full control of the machine but are taking action based on information provided to them.
- Remote operation is when a machine is operated remotely by an operator. This can be while in line of sight of the machine and working environment, or non-line of sight where the operator is in a different location. Removing the operator from the machine reduces the exposure to a hazardous environment.
- Semi-autonomous operation means that part of the machine (or sub-system work cycle) has been automated or can operate automatically. Semi-autonomous technologies can allow an operator to control multiple machines (usually up to 3) from a remote location.
- Autonomous operation means that the machine is fully automated and operates independently under remote control of the main system network and supervisory software. As few as two operators can manage a whole fleet of vehicles.

At each level, automation assists operations making them more consistent and predictable and increases safety for people and the machines and raises productivity. This is valuable for the mining companies although the actual levels of improvement are unclear and data on actual detail of delivery is limited with few properly controlled comparisons.

We are also now seeing the same technology used for autonomous truck hauling (AHS) starting to be used to automate other operations in the surface operation and in underground mines. However, full autonomy in the underground mine is not as advanced as in the surface mine.

As yet, no true artificial intelligence has been applied in the autonomous mining industry, but it is an opportunity for the future. When AI is applied to autonomous mining trucks, they will be able to monitor, learn from, adapt and educate other trucks in the mining environment. This could result in even more productivity and reliability improvements.

Autonomous Truck Haulage Systems

AHS have evolved from improvements in GPS for positioning and navigation, developments in sensors and detection – particularly radar and LiDAR, improved computing power and on-board monitoring, faster and more reliable networks and internet connection, and the development of effective and accurate algorithms and software. AHS has appeared first at large mine operations where the benefits have the largest impacts, due to the high component of fixed costs, and in developed countries where there is a shortage of skilled workers and labour costs are higher.

The first commercial autonomous mine haulage systems were launched in 2008 by Komatsu and 2011 by Caterpillar, the two main leaders in this technology. Some other mine haulage truck companies, such as Hitachi and Volvo (Terex), are also developing AHS but are at earlier stages of development and penetration. The current systems continue to evolve and, so far, have only been employed at a handful of very large mines, but reportedly very successfully. Productivity improvements of around 15-20% have been reported along with maintenance savings, tyre life improvements, and equipment life improvements, as well as significant safety benefits.

Figure 2: Komatsu 930E haul truck

Source: Komatsu

The operational savings come from lower overall labour costs, accurate dispatching systems, reduced cycle times, and the elimination of shift changes and breaks required for manual operators. Autonomous operations eliminate the truck operator, but this is offset with an increase in technical support staff. For a typical shift roster this results in a headcount reduction per truck of 4, with an increase in technical and operating support staff of about 1. Overall, autonomy significantly increases the consistency of the operation and raises the overall truck utilisation. The effective utilisation for a manned fleet is typically about 60% and for autonomous operations increases to around 75%, although not all autonomous pits can sustain this [1].

Figure 3: Caterpillar 793F haul truck

Source: Caterpillar

At the same time, some reduction in operating and maintenance costs can be achieved from consistent and optimum driving, and less unintentional equipment abuse and damage (caused by driver fatigue and distraction). There is also some reduction in unscheduled repairs, although there are no measurable increases in component life observed. There may be some fuel consumption improvement with autonomous operations, but it is very difficult to quantify and highly influenced by the operating conditions. Further, while there is not reduction in tyre wear from autonomous driving, there is an increase in tyre life from reduced operator-induced damage and improved road maintenance required for autonomous trucks to operate. These factors, combined with better knowledge and understanding of the machine through on-board machine monitoring and diagnostics systems, lead to lower operating and maintenance costs and higher machine availabilities.

Higher availability and utilisation results in fewer trucks being required, with the potential to reduce fleet sizes and associated capital expenditure or allows more tonnes to be mined from the existing fleet. These factors can increase productivity and lower unit costs.

From a safety perspective it also removes staff from operations and exposure to risks. These risks include dust, noise, vibration and physical injury. An AHS system has multiple layers of system functionality to detect hazards. Only dedicated AHS equipped vehicles operate within a defined autonomous operating zone, which may be the entire mining area, including waste and ore dumps, or a well-defined section of a mining area. All vehicles entering the autonomous zone are equipped with GPS transponders for tracking and staff required to operate in the AHS mining area can be detected through wearable technology and Caterpillar also supplies an 'A' stop: an emergency device that can stop all vehicles within 300m. Komatsu reported zero serious injuries at the end of 2018 after 10 years of autonomous vehicle operation [(2)].

One significant challenge faced by the mining industry is operating and staffing mines in remote locations. Autonomous and semi-autonomous machines allow the staff to work away from the mine in larger towns or cities and live in the comfort of their homes and with their families. This also reduces the need for fly in facilities at operations and/or additional infrastructure at the mine to accommodate this staff. It also allows the mining company to recruit from a larger pool of candidates in the cities. Some people question the social licence of removing equipment operators, but it does increase the employment of higher skilled employees operating the systems and some companies are using it as an opportunity to retrain and upgrade the skills of existing staff. Fortescue Metals states that workforce skills development has been a significant aspect of planning for the expansion of automation, and the implementation of a staged, sustainable redeployment process has already permanently assigned team members to new roles.

Overall, improvements in truck productivity can have a variety of benefits to safety, the operating and capital costs of a mine site, and ultimately the economics of the operation. Lower costs may also allow for a lower cut-off grade, lead to an increase in reserves, and result in an increase in the overall pit size and life of mine. Finally, all of these factors are likely to lead to a reduced carbon footprint for the mining company.

Autonomy pathway

An AHS is a complex system of components and technology which requires additional capital expenditure for the equipment. However, operating OEMs and mining companies all stress that it also requires a change of culture, a lot of planning, new safety procedures, and high levels of management focus for optimal implementation.

The implementation of an AHS requires significant capital expenditure and comprises a number of fixed and variable costs. Fixed costs apply to the site installation and include the control room, AHS software and configuration, communications upgrades and infrastructure, ancillary equipment, and associated staff. There is also a fixed cost for equipment per truck. Depending on the manufacturer, the truck components can include LiDAR, multiple radars, an inertial measurement unit, vehicle controls (steering, braking, throttle), control computers, high precision GPS, cameras, and communications devices. Variable costs depend on the number of vehicles installed within the system. The total cost is therefore determined by the scale of implementation.

The primary factor influencing the size of truck being used, or converted, in an AHS is the cost of the technology. The cost of the autonomous components is the same whatever the size of the truck. Thus, there is a higher economic benefit with a larger capacity truck.

Komatsu's system uses two applications called FrontRunner and Dispatch [3]. Komatsu has its primary control technology located centrally and the technology manages all the trucks as a fleet. The central control system has visibility of every machine in the autonomous zone and controls all the trucks. The central system manages both the destination assignment and detailed path planning for the trucks. The system manages and alerts for any potential autonomous-to-manned interaction.

Caterpillar's autonomous system is called Minestar [(4)], and comprises a number of separate systems (Fleet, Terrain, Detect, Health and Command) that are building blocks to final autonomy. Caterpillar has the primary control technology located on the mining truck. The central control system does not necessarily need, or have, visibility of all the machines in the autonomous zone. The central system assigns the trucks, but they manage their own path. The trucks monitor and manage their interaction with other autonomous trucks and any manned vehicles in the autonomous zone.

The two companies' systems operate differently from a technical perspective but functionally operate in the same way. The different systems mean that the costs for the central control system and onboard systems vary, as do the licence fees, but overall the costs are reported to be similar, but will depend on the fleet size. Both systems can be retrofitted to existing vehicles and be built into another manufacturer's equipment, although Komatsu has yet to be retrofitted on a non-Komatsu machine. Caterpillar notes that this allows a mine to approach autonomy in a number of stages.

Mines and systems in operation

Both Caterpillar and Komatsu began AHS programmes in the 1980s, but it wasn't until 2008 that Komatsu commercially deployed the first AHS for the mining industry at Codelco's Gabriela Mistral copper mine in Chile. Caterpillar started its first real field trial at BHP Group's Navahoe coal mine in New Mexico, USA in 2011.

Figure 4: Hitachi truck

Source: Hitachi

In 2013, Caterpillar commenced installation at BHP's Jimblebar iron ore mine in Australia. Also, in 2013, AHS was installed at Fortescue's Solomon iron ore hub in Australia. In April 2018, Fortescue announced the expansion of its AHS fleet, with the first AHS trucks in operation at Christmas Creek mine (part of the Chichester Hub). It further plans to convert about 100 haul trucks at the Chichester Hub which will see Fortescue become the first iron ore operation to have a fully autonomous fleet.

By early 2019, Caterpillar also expects to have 13 Cat 793F autonomous trucks running at Vale's Brucutu iron ore mine in Minas Gerais.

After success at Codelco, Komatsu then began operating AHS at Rio Tinto's West Angelas iron ore mine in Australia in 2010 and Rio Tinto now uses AHS across six sites in the Pilbara region, including the recently commissioned Silvergrass mine. In the oil sands in Alberta, Canada, Suncor Energy announced at the beginning of 2018 that it was proceeding with a phased implementation of AHS at company operated mines, starting with the North Steepbank mine. Last reports stated that it was operating a fleet of 20 autonomous 930E-AT and 980E-AT models and over the next five years expects to deploy more than 150 autonomous electric haul trucks in the full programme. Komatsu currently has more than 130 autonomous trucks operating worldwide.

Rio Tinto is currently expanding its autonomous fleet in the Pilbara, Australia. A total of 29 Komatsu haul trucks have been retrofitted with AHS technology for completion by mid-2019. A further 19 Caterpillar haul trucks at the Marandoo mine are being retrofitted for completion by the end of 2019. This is the first time AHS technology has been deployed by Rio Tinto on Caterpillar haul trucks. This increases Rio Tinto's number of AHS enabled trucks from around 80 to over 130, equivalent to about 30% of the fleet of almost 400 haul trucks in the Pilbara.

Figure 5: Liebherr T284 mining truck

Source: Liebherr

In 2013, Hitachi implemented its first AHS trucks at Stanwell's Meandu coal mine in Australia. This was a proof of concept site trial using three EH5000 trucks which was successfully completed at the end of 2017. Hitachi is leveraging technologies developed for its parent company Hitachi Ltd's automotive and railroad solutions, as well as Wenco's fleet management and dispatch system. Hitachi is planning a commercial release of an autonomous trucks sometime in the near future and is looking to deploy a fleet of EH5000 trucks at Whitehaven in NSW, Australia.

Volvo (Terex), Liebherr, and BelAZ are also developing AHS but these companies are at an earlier stage of development. In 2018, Volvo signed an agreement with the Norwegian mining company Brønnøy Kalk, where a Volvo AHS will carry limestone on a three-mile route between the mine and its closest port. The system is expected to be fully operational in 2019. In Morocco, a Terex mining truck with an AHS control developed by the Russian company VIST Robotics (part of Zyfra Group) has successfully completed trials at a special test site (5). In Russia, autonomous trucks from BelAZ are already used in the quarry operated by the Siberian coal and energy company in Khakassia. At the moment, the first AHS truck has been assembled and operating successfully in an offline mode. Other haul truck manufacturers such as, ETF, and XEMC have yet to announce AHS programmes.

Liebherr unveiled its autonomous haulage solution in Germany, at the end of 2017. Initial prototype testing started in 2016 and Liebherr plans to begin field trials at a customer site in 2019. Liebherr intends to provide an open architecture allowing customers flexibility with respect to the level of OEM content and integration from Liebherr to compliment customers' existing investments in fleet management and telemetry. This approach will allow its customers to use Liebherr products along with other OEM equipment and choose the most suitable suppliers for third party solutions.

The most prominent non-OEM producer of autonomous equipment is Autonomous Solutions Inc. (ASI). In mid-2018, ASI began work on a project with Barrick Gold to retrofit and automate a fleet of haul trucks at the company's Arturo operation in Nevada. During the initial phase of the project ASI retrofitted five Komatsu 930-E Ultra Class haul trucks to autonomous operation at the mine. This phase will consist primarily of waste haulage, prior to moving into production. Subsequent phases will follow with potential expansion to additional trucks. Barrick reportedly chose ASI as a partner for their ability to provide an agnostic product that can be adapted to any manufacturer's equipment and to different mine layout and practices.

ASI is a leading player in vehicle automation in a wide range of industries. ASI's Mobius platform provides an OEM-agnostic, interoperable command and control software solution for autonomous vehicles. Mobius enables mine operations to integrate a variety of mining vehicles under its platform. ASI's robotic hardware and software systems allow users to safely manage their entire fleet of vehicles autonomously.

Australian-based RCT offers a versatile range of automation and control solutions for surface and underground equipment (6). This ranges from the automation of a single machine to a full autonomous fleet. The ControlMaster range is fully scalable, permitting upgrades from a line-of-sight solution, to teleremote, through to a fully autonomous fleet. In addition, RCT's automation path allows the combination of technology available to deliver the full solution including; automation, traffic management, people and asset tracking, and fleet integration. The full combination is called Infinite. RCT's packages are customisable for any make or model of machine.

Sample projects include dozer line-of sight implementation at Rio Tinto's Bingham Canyon mine, USA, teleremote installation at Codelco's Andina mine in Chile, and dozer teleremote application at Hancock Prospecting's Roy Hill mine in Australia. In March 2019, RCT successfully installed its autonomous technology on the recently released Sandvik LH621i underground loader in Western Australia. RCT is a full-service company, offering clients the complete package with all its proprietary products. Including: skills training, parts, technical and customer service support in 64 countries worldwide.

Canadian-based Nautilus International designs and manufactures fully autonomous guidance systems for mining and other custom applications (7). Nautilus International provides radio controls, teleremote controls, automated guidance systems and proximity safety systems which are specifically designed to increase safety and productivity.

Caterpillar and Komatsu were strategic early movers and fortunate that they were able to partner with mining companies to develop their products. Fortescue Metals and Rio Tinto played a significant role in developing the autonomous mining truck fleets for the two dominant suppliers. To develop viable autonomous mining truck alternatives, current and future suppliers will need to partner with an operator. The two emerging mining truck suppliers are doing this but are nearly a decade behind and do not have significant truck fleet numbers in the industry. Further, the niche autonomous suppliers are partnering with existing established or developing autonomous truck suppliers, and this is likely to continue (1).

Cost benefits of AHS

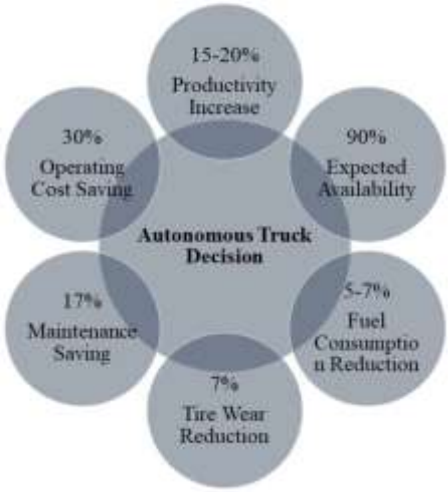
Outlining the potential benefits of AHS is straightforward, but finding hard data is more difficult. This is because every mine is different and the mining companies and OEMs that have so far implemented AHS have rightly guarded this proprietary information. The companies have made some suggestions about the scale of improvement but the definitions of what is included are not clear.

In December 2017, Caterpillar (8) highlighted in a webinar the step change in productivity and safety with AHS and stated increases in productivity in the order of 15-20% compared with manual haulage trucks. In April 2018, Fortescue Metals (9) reported that since the introduction of AHS at Solomon in 2013, the trucks have moved over half a billion tonnes of material and have achieved a greater than 30% increase in productivity levels.

In May 2018, Komatsu (2) reported that AHS-enabled customer productivity has improved, reducing load and haul unit costs by more than 15%, compared with conventional haulage methods. In August 2018, Chris Salisbury (10), Iron ore chief executive stated that autonomous haul trucks can operate for an additional 1,000 hours per year each and had reduced operating cost by 15% in comparison with conventional manned haul trucks. Further, in the ten years of operation the company had experienced a perfect safety record.

A paper in August 2017 by Gölbaşı and Dagdelen from the Colorado School of Mines Department of Mining Engineering (11), suggested benefits shown in Figure 6.

Figure 6: Expected benefits of Autonomous Mining Trucks (2017)



Source: Onur Gölbaşı and Kadri Dagdelen, Colorado School of Mines Department of Mining Engineering

For an existing mine, the implementation of an AHS is a comparison of the increased capital costs against the savings in operating costs and the less easily quantifiable benefits to safety. The initial site set-up costs can range up to US$20m and autonomous component installations on the mining trucks will vary with supplier but can range up to US$1m [1].

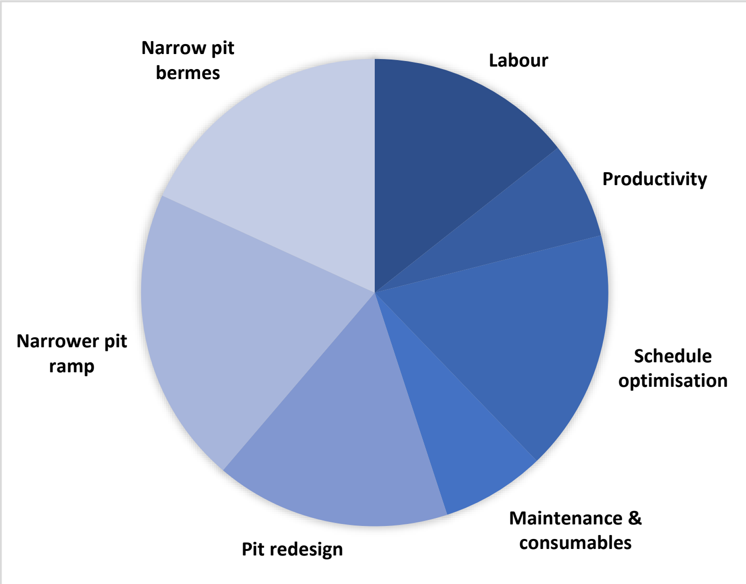
In a simplified analysis of the cost benefits of operating an AHS, a paper in November 2016 by Richard Price of Mining Technicians Group Australia (MTGA) [12], a company that has been involved in most of the autonomous haulage projects in the Pilbara, examines a theoretical application of an AHS in a medium scale mine site.

The paper assumes that a mine site has 10 x 180t trucks and 14 ancillary vehicles engaged in the AHS. The cost of converting the haulage fleet and associated infrastructure to AHS is A$18.5m. The annual employment cost saving is A$2.7m, the annual tyre cost saving A$1.2m, and value of increased production at $A22.5m, although the paper did not address maintenance cost savings. It demonstrated a net benefit is A$8.2m with 85% of the cost savings coming from improved productivity.

The report concluded that an AHS system has cut-off thresholds that limit its application to large open pit mines. The results indicated that a mine needs to have in excess of 12Mt/y of total earthmoving. Also, there are truck count cut-off thresholds, and while these vary according to payload capacity, a minimum of 6-8 trucks is generally required. The cost of the autonomous components is the same whatever the truck payload and so there is higher economic benefit with a larger capacity truck.

In February 2018, Whittle Consulting [13] produced an AHS financial model assessment for MTGA on a hypothetical new surface mining operation with an NPV of A$479m. It not only considered the operating cost savings from using an AHS but included pit redesign which included allowing the narrowing of pit ramps and catch benches to steepen the overall pit wall.

Figure 7: AHS cost savings for a new open pit mine



Source: Whittle Consulting

The first improvements to NPV are cost savings to variable, fixed, and potential capital costs (productivity). The report showed that after an AHS capital cost of A$21m, these cost reductions total a net A$73m and improve the mine NPV to A$551m, an increase of 15%. Significant further improvements of A$115m arise from re-optimising the pit design which increases the NPV to A$666m, a total increase of 39%.

Clearly the benefits of AHS are significant, although the actual benefits appear variable from mine to mine and possibly subject to some debate. Important factors in the success appear to be the level of management commitment, planning, and focused implementation, with the best results reported from well-operated mining sites. Equipment differentiation is harder to identify at this stage.

Practical experience with AHS

Practical experience with AHS continues to develop and improve and in practice, autonomous truck fleets have surprisingly produced variable results (see cost benefits of AHS). However, details on operating experience and issues are not widely available outside of a few technical papers and consultant reports. James Petty of iTi Solutions [(1)] notes that both systems are well proven and have delivered excellent results. Both suppliers have successfully supported multiple deployments, are well resourced, and have highly competent teams. Unfortunately, both systems also have examples of less-than-expected performance.

Points highlighted by available feedback state that an autonomous truck fleet is an operating tool, not a technical solution. The key to getting a great result from autonomous fleets is to have a well-operated site. Autonomous fleets will not compensate for poor operations and they cannot be used to 'buy' good operations. Getting expected autonomous fleet results often requires a business transformation with a culture change, along with the technical change. The technical component is relatively straightforward compared with the culture change [(1)].

It is also reported that the ramp-up period for AHS trucks can take time and to operate on par with manned equipment it is likely to take 6-12 months [12]. Furthermore, the average cycle time of an autonomous truck will not always match the best cycle time that a skilled operator can deliver, but the cycle time will be better than an unskilled operator and it will be 100% predictable, with no variances or errors [14].

One minor issue is WiFi dropout if there are shadows in the system. This happened in February 2019 at Fortescue's operations when there was a minor collision between two AHS dump trucks when the WiFi dropped out.

Frequent industry news on autonomous equipment makes if feel that autonomous fleets are widespread in the industry, but the technology has only been implemented in a relatively small number of mines so far. Autonomous haul trucks are still in the early adoption stage by mining companies.

The next developments in AHS

Komatsu has showcased its new unmanned autonomous haulage vehicle which does not feature an operator cab. The vehicle also only has four wheels (rather than six), distributing the load equally across the wheel base, both when the vehicle is loaded and unloaded. By adopting a four-wheel drive system, retarder and steering, the vehicle is reported to achieve high-performance shuttling in both forward and reverse travel directions.

Figure 8: Komatsu Concept AHS Mining Truck

Source: Komatsu

While the trend in recent years has been for larger and larger trucks, it has been suggested that the largest trucks may not be the optimum configuration size for some autonomous mines, especially in deeper open pit mines. This is because smaller, more efficient AHS trucks with higher passing tolerances means that haul roads could be narrowed and have steeper ramp grades which could allow the pit design to have steeper overall pit wall angles and therefore a lower mine stripping ratio. Depending on the geology of the orebody, the benefits could be significant as demonstrated in the Whittle financial model above.

Manufacturers are also enhancing the AHS' mixed-operation functions, enabling manned trucks of any make to interoperate with AHS trucks in a blended operation. Some manufacturers are also working with industry operators towards standardisation of interoperability between different AHS systems, to improve safety and efficiency at customers' operations.

Meanwhile, upgrades to existing systems continue as technology improves. One such area is the network where mining operators demand wireless networks with high-availability, seamless mobility, and the ability to support multiple applications and services simultaneously. Accordingly, the industry is moving away from less predictable wireless technologies such as Wi-Fi, and towards private LTE (long term evolution) networks, that improve security, capacity, and overall performance within a multi-application environment. In addition, with an LTE communication network, large areas can be covered with a fewer number of LTE base stations than Wi-Fi access points. In addition, the network configurations are simpler, and LTE has inherently been designed for fast roaming with high data transmission performance.

So far, no production sites have operated on an LTE network, but in January 2019, Komatsu announced that its FrontRunner AHS had qualified to operate on Nokia's private long-term evolution (LTE) mobile broadband technology. This is the mining industry's first AHS enabled system to be able to be run on a private LTE in commercial operation. In December 2018, Epiroc signed a cooperation agreement with communications technology company Ericsson to jointly help mining companies achieve optimal wireless connectivity in their operations through LTE and 5G technologies.

Pace of Future Implementation

AHS for surface mines now appears relatively mature and has been successful in improving productivity and safety. The technical issues appear relatively minor, there is interest across the industry, and the role out to other mines globally is now the next step. However, this does not appear to be happening at any pace and there a number of possible explanations of why more mines are not now using AHS.

There are likely a number of reasons, including a lack of understanding of the technology and limited personnel with the requisite experience, skills, and training throughout the industry's hierarchy. Further there are is a shortage of skilled autonomous operators, developers, and consultants, some of who are moving to the autonomous auto market.

We believe there are likely to be some limitations on equipment supply from OEMs on new equipment and truck conversions, which will allow the OEMs to be more selective in their customers. However, if the existing suppliers do not develop additional capacity quick enough this could create opportunities for additional entrants in to the market.

Capital availability could also be an issue (although it is less tight than it has been in recent years) and while low margin operations might struggle to finance the capital, the uplift in relative profitability could be transformational, with relatively quick paybacks.

Finally, the historical conservatism of the mining industry is also likely to be a factor. There is still a natural reluctance within the industry to adopt new or unproven technology due to the high capital cost involved and the potential operational and reputational risks involved.

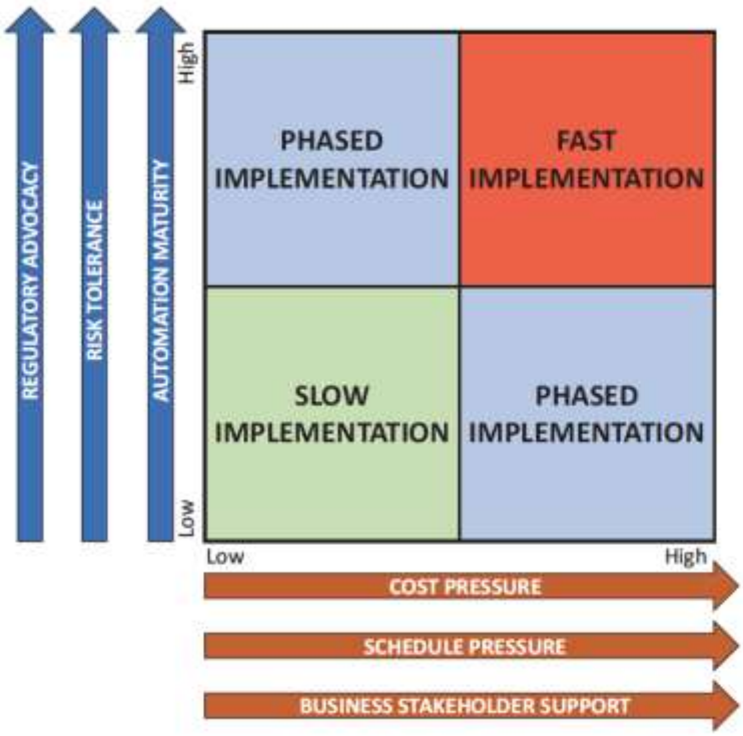
New Guidelines for AHS

It is worth noting that Global Mining Guidelines Group (GMG) is planning to publish a globally relevant guideline for the implementation of autonomous systems in mining [(15)]. This project will enable global mining companies and OEMs to adopt and successfully implement autonomous mining systems with the aid of common practices. It aims to communicate and educate and covers the following key areas:

- Functional capability
- Functional safety
- Change management
- Communications with the workforce and the local community
- Interactions with regulators

This guideline will be an expanded checklist, providing mining companies and OEMs with the tools for the implementation of autonomous mining from planning to final stages. Drawing on lessons learned from other industries, it covers new and existing mining operations, all stages of material processing, and various levels of autonomy.

Figure 9: Factors Influencing the Choice of Implementation Approach for AHS



Source: Global Mining Guidelines Group

Automation of Other Surface Mining Equipment

The same technology being used for autonomous truck hauling (AHS) is now starting to be used to automate other equipment in the surface mine, including drill rigs, dozers, loaders and ancillary vehicles. Much of this equipment is currently, at best, semi-autonomous, although a few mines have implemented fully autonomous drill rigs and dozers.

Autonomous surface drilling

Drill rig automation in production in the open pit is being implemented with success. Drilling is about precision and integration with GPS which allows drilling pre-programmed blast hole patterns with a high drill hole accuracy and repeatability. This reduces costs, consumables, and explosives and produces a more reliable and consistent fragmentation. As a result, it increases shovel productivity, improves truck loading, crusher throughput, and reduces maintenance throughout this chain.

Rio Tinto was reportedly the first company to implement autonomous drilling. Its Autonomous Drill System (ADS) enables an operator using a single console at a remote location to control four autonomous drill rigs from multiple manufacturers simultaneously. In mid-2018 it was reported that Rio Tinto had deployed four drills retrofitted with autonomous drilling system technology at its Yandicoogina mine in the Pilbara, Australia, in addition to the existing seven at West Angelas mine, with plans to add a further nine rigs by the end of 2018, bringing the total fleet to 20.

In 2015, Rio Tinto reported that its seven autonomous rigs had drilled over 2.25 million metres and delivered productivity improvement of about 10%. Rio Tinto reports that it also uses its own 3D visualisation technology. RTVis delivers real-time 3D models of ore deposits located far beneath the surface that previously couldn't be measured. This enables more accurate drilling and blasting, reduced explosive use and better waste classification [16].

BHP Group has also trialled automated drilling technology using Pit Viper 271 rotary blasthole rigs supplied by Epiroc (Atlas Copco) at the Yandi mine in Pilbara. BHP Group reported a 20% improvement in drill efficiency, including a 10% increase in metres drilled per shift and a 22% improvement in drill bit life. Beyond the obvious savings in labour costs, there has also been much greater utilisation of equipment as the drills operate during breaks and shift changes that traditionally result in down time.

As a result of the successful Pilbara trial, BHP Group ordered autonomous upgrade packages for a further 18 of its rigs which were completed by mid-2017. The 20-strong fleet is controlled at the company's five iron ore mines in Pilbara, with the longer-term aim of remote operation from a base in Perth. Since then an autonomous drill rig has started operating at the South Flank mine where BHP Group is targeting first production of iron ore in 2021. The company plans to operate five autonomous drill rigs at South Flank.

Figure 10: Epiroc Rotary Blast Drill Rig PV-351

Source: Epiroc

Epiroc also operates a Pit Viper autonomous drilling fleet at the Penisquito gold-silver mine in Mexico, operated by GoldCorp and Anglo American has ordered a Pit Viper 351 and SmartROC D65 autonomous drilling fleet to be used at its new Quellaveco open pit copper mine in Peru for delivery in 2020 and 2021.

Caterpillar offers the MD6250 rotary drill which can be integrated with Cat MineStar, and with the addition of Cat Command for drilling is capable of drilling in autonomous mode. An operator seated at a remote station designed to mimic the drill's cab can control up to three drills at the same time, programming them to drill single rows autonomously. In 2017, Caterpillar highlighted in a webinar a 40% productivity improvement from automated drilling [(8)].

Sandvik offers AutoMine Surface Drilling [(17)] which offers high drilling productivity and equipment utilisation for its i-series drill rigs from the safety of a remote operation centre. One operator can control a fleet of drill rigs, and the package includes 3D drilling navigation to maximise blast accuracy and mine efficiency. The product allows mines to drill more holes in less time, while significantly increasing safety and drilling performance.

ASI also offers an autonomous drilling system. Multiple drills may be operated and monitored from a command centre remote from the bench. The holes are drilled in a pre-mapped order at the locations and depths loaded into the system. The drill is precisely guided to the proper hole coordinates for accurate hole location. Upon reaching the desired depth it retracts the drill string then jacks and propels to the next hole.

In addition to autonomous drilling, ASI's Mobius for Blasting platform provides capability for remote, semi-autonomous, or fully autonomous navigation of blast vehicles including blast factory and stemming vehicles. Mobius is capable of working with various third-party payload providers to enable automated deployment of blast mediums and initiation systems.

Potential integration of blasthole characteristic data such as seam and geology aspects of each hole allow dynamic blast charging and detonation timings during the blast cycle. By dynamically tailoring the blast process based on actual, "as-drilled" hole data, blast processes can achieve higher efficiency and increased fragmentation. The resulting benefits ultimately include less impact on excavators, crushers, grinders, and even more efficient haulage.

Through existing product updates and new product development, Joy Global (Komatsu) has been automating its P&H blasthole drill line, with a number of features now available on its P&H 77XR blasthole drill. These include a tele-remote system that offers single-unit remote control operations; high precision GPS navigation and validation; auto hole-to-hole navigation that will allow for obstacle detection and avoidance; and drill production monitoring. The line of sight remote operator interface can be controlled up to one mile away and the high precision GPS provides less than 10cm hole location deviation.

Autonomous dozers and tractors

Autonomous dozing is being trialled for some applications, particularly in civil applications, but is currently being used semi-autonomously at mining operations. Among different types of operation carried out at mining sites, one area where autonomous dozing is being investigated is the waste dump area operations. Semi-autonomous dozing is being used in production areas at open pit coal mines.

Figure 11: Komatsu Dozer D375A-8

Source: Komatsu

Komatsu's iMC system for dozers is currently available on a number of its dozers and allows these machines to carry out both bulk and final trim dozing in fully automatic mode from start to finish, delivering final grade performance and accuracy throughout the job with significantly increased productivity and efficiency.

Caterpillar has implemented semi-autonomous dozers in the coal operations in the Powder River, USA, and in Queensland, Australia. The D11T dozers operate around existing draglines, helping to feed the dragline. They have increased consistency, productivity and utilisation, as well as removing operators from a hostile work environment (particularly vibration and steep grades).

Arch Coal is improving the consistency of its dozing operations at Black Thunder coal mine, Wyoming, USA with the implementation of Cat Command for dozing. In Australia, Wolff Mining is operating semi-autonomous Cat dozers at an open-cut coal mine near Blackwater, Queensland. The semi-autonomous system allows one operator to control up to three machines at one time from a remote location.

Teck has deployed a remotely-controlled dozer and backhoe at its Coal Mountain operations in Canada to access areas which would be hazardous for an onboard operator. The dozer and backhoe are driven by an operator using a joystick system, in a custom-built control cab that has a view of the operating area. The operator can also see what the dozer sees via four cameras mounted on the machine, and a series of monitors in the control cab.

Automation of surface loading equipment

The automation of earth moving machines provides another step to increased productivity within the mine. However, loaders face additional challenges as a result of the variability of the loading face and the risk of collisions with the haulage trucks. Due to the complex nature of the bucket-media interaction, developing automatic loading functions that are better than or equal to expert manual drivers with regard to performance is a highly difficult task.

Figure 12: P&H 4100 Electric Rope Shovel

Source: Komatsu

Currently the operation of heavy loading equipment is largely manual, but many aspects of the loading cycle are now able to be automated to produce guided, remotely operated, and semi-autonomous operation.

A prototype operator assist technology for dragline excavation sequencing is being developed and trialled by researchers at the University of Queensland, with funding from the Australian Coal Industry's Research Program (ACARP), and in collaboration with Brisbane-based Mineware. The technology provides guidance to operators on where to position the machine, where to dig material and where to place the material to unload. This is a step towards eventual automation of draglines but could also be used as a decision support tool that improves operator technique [18].

In Australia, Mining3 has been working with a number of participants since 2007 on a Shovel Load Assist Program (SLAP) for electric mining shovels [20]. Mining3 is a leading research organisation, directed by its global mining industry members to develop and deliver transformational technology to improve the productivity, sustainability, and safety of the mining industry. While the ultimate goal is to fully automate the process of loading material into waiting trucks in a way that optimises tray capacity and distributes the load equally, SLAP currently addresses the safety risks associated with manually controlled machinery by providing a layer of automated protection to the operator. SLAP's five operator assistance technologies offer increasing levels of automation, improve safety, reliability and productivity, and reduce the amount and extent of maintenance required. This is marketed through Komatsu Australia.

Caterpillar can deploy its Cat MineStar system for its electric rope and hydraulic shovels and wheel loaders as well as enhanced diagnostic capabilities and providing detailed troubleshooting functions, although the autonomous Command feature is not available.

Some observers suggest that the implementation of fully autonomous surface loading is still some five years away, while others believe that full automation is unlikely.

Ore sensing for shovel buckets

While not strictly automation, it is worth mentioning recent developments in ore sensing for shovel buckets.

In 2017, Teck partnered with MineSense for the first full-scale trial of bucket-mounted ShovelSense technology at its Highland Valley copper operations in British Columbia [(19)]. Sensors are mounted on the shovel bucket and use x-rays to tell the difference between waste rock and valuable ore, one shovel load at a time. The sensors, combined with analytics, provide real-time information to determine whether the load is worth sending to the mill for processing, or for handling as waste rock. Decisions that were once a matter of informed estimates can instead be based on real time data, leading to improved mill productivity, reduced energy use and lower water consumption. The sensors are now in use on two shovels.

In another project, the University of Queensland is working with Brisbane-based PlotLogic, supported by funding from the Minerals Research Institute of Western Australia (MRIWA), to identify ore waste boundaries for gold and iron ore at the point of excavation using hyperspectral imaging. This offers new precision in knowledge of the orebody and has the potential to incorporate accurate ore mapping into daily workflow, increase recovery, reduce dilution, enhance mining to plan and facilitate short-interval control [(18)].

Autonomy in Underground Mining Equipment

As with surface mining, full autonomy remains the goal of the underground miner. Mining companies and contractors are constantly looking to use technological developments to better utilise their investment in equipment and human resources and improve safety. Particular features of traditional underground mines are: long unproductive periods caused by re-entry times required for operators after blasting; and higher health and safety risks due to various geotechnical and environmental challenges. The use of autonomy underground aims to increase the productivity of the equipment and improve the safety of the operators.

Full autonomy in the underground mine is not as advanced as in the surface mine. Haul trucks are used less frequently in underground mines, although a few mines are using haul trucks with AHS. More underground mines perform a short cycle of loading, hauling and dumping from a draw point to a tipping point with LHD equipment. Implementation of autonomous systems underground for LHDs is occurring, however, as with surface loading, one of the major hurdles to automating LHDs is replacing human judgement required for filling the bucket. As a result, fully autonomy is being used for the hauling and dumping cycle, but semi-autonomy is usually used for loading. Successful trials of fully autonomous LHDs have been achieved and Sandvik i-series now offers an automated bucket filling assistant as a standard function. Underground drilling operations are also achieving increased levels of autonomy but are also only semi-autonomous.

The implementation of varying levels of autonomy is increasing in underground mines, with one important factor being the implementation of improved communication infrastructures. This has allowed new machines to be equipped with computerised control systems which enable a large number of automatic functions to be added. It appears that many of the implementations are being taken in a step-by-step process and there are few examples of full-scale implementation. Further, there is limited available information about the level of improvements in productivity, or cost savings that have been achieved, to encourage further implementation.

Today's Modern Underground Mine

One of today's most automated underground mines is Resolute Mining's Syama gold mine in Mali (21) which is using a truck haulage system and loaders. Production commenced in December 2018 and the mine has been designed in conjunction with OEM Sandvik Mining (22) to ensure it is able to accommodate the best available technology for mining, haulage and processing. A high capacity fibre optic system has been installed underground throughout the mine. This will allow the operation to install sophisticated mobile equipment monitoring and guidance systems, which are expected to improve safety and productivity in the mine. The design of underground loading points and ore passes has also been influenced by current trends in mobile equipment operation and automation technology. As these technologies develop their use will be progressively incorporated into the operation of the mine.

Sandvik is delivering to the mine its systems for planning, analysis, process optimisation and automation, including AutoMine and a full fleet of Sandvik TH663i trucks, LH621 loaders, DL421 autonomous drills, and electric LHDs. Sandvik's TH663i truck is designed for intelligent mine operations and improved productivity and comes automation-ready. Sandvik's AutoMine Fleet is an automation system for a fleet of underground loaders and trucks sharing the same automated production area. It provides automatic mission control and automatic traffic management for the equipment fleet, while system operators remotely supervise the process.

The mine is also using Sandvik's OptiMine 3D Mine Visualiser which brings a three-dimensional model of the mine layout directly to the surface office, which enhances the comprehension of the mining environment. Sandvik will also deliver a full OptiMine platform to Vedanta Zinc's Black Mountain Mining operations in in South Africa, and Hindustan Zinc's Sindesar Khurd mine in India in 2019

Randgold has been operating Sandvik's AutoMine at its Kibali mine in the Democratic Republic of Congo, along with three semi-autonomous LHDs where one operator now has the ability to control up to three separate machines on multiple levels throughout the mine from the surface. In Canada, Agnico Eagle has been operating AutoMine at its LaRonde mine with one LH517 and one TH551i with an LTE network. In Australia, China Molybdenum has been operating Sandvik Automine since 2010 at the Northparkes mine. Operators located in a surface control room load ore at underground drawpoints using manual teleoperated control. The loader is then switched to automated mode to travel to the run-of-mine bin where the ore is dumped autonomously. The loader then autonomously returns to the next drawpoint selected by the operator. Each of three operators is typically responsible for three loaders. Productivity benefits include the ability to continue to mine through shift changes and blasting, resulting in a 23% improvement in daily tonnes produced [23].

Figure 13: Sandvik AutoMine semi-autonomous control

Source: Sandvik

Autonomous tramming and teleremote operation are used at Barrick's Hemlo mine in Canada. The company is running an Epiroc Scooptram ST14 loader from surface and has been running an autonomous truck circuit since 2007. These enhance the workers' safety while reducing ventilation and climate control requirements underground.

Leading Underground OEMs

The leading OEMs in the automation of underground mining equipment are currently Sandvik, Epiroc (formerly Atlas Copco), Caterpillar, Komatsu (through its Joy range of products), and Boart Longyear.

Sandvik Mining and Rock Technology is a business area within the Sandvik Group and a global leading supplier of equipment and tools, service and technical solutions for the mining and construction industries. Application areas include rock drilling, rock cutting, crushing and screening, loading and hauling, tunnelling, quarrying and breaking and demolition. Sandvik operates a test mine in Tampere, Finland.

Epiroc is a leading supplier of mining and rock excavation equipment. Epiroc was spun out of Atlas Copco in June 2018. Epiroc has been strengthening its position in the autonomous market through a number of acquisitions and collaborations, including a stake in Mobilaris (software solutions), a letter of intent with the defence and security company Saab and its subsidiary, the technology consultancy Combitech, and a 34% interest in ASI Mining (a subsidiary of ASI) in order to scale ASI Mining's autonomous mining platform and give it access to Epiroc's world-wide service and support channels.

On the underground side, Caterpillar offers a broad product line including drills, loaders and trucks for hard rock applications; customised systems for longwall mining; and precision-engineered products for room and pillar operations.

Komatsu supplies underground mining equipment through its subsidiary Joy Global which it acquired in 2017. Joy is the largest manufacturer of machines used underground. Komatsu offers an extensive product suite of hard rock mining equipment, including hydraulic jumbo drills, in-the-hole production drills, drifters, loaders, and trucks. In addition, it offers a full line of raiseboring tools and blasthole drilling tools.

Boart Longyear is a leading provider of drilling services, drilling equipment and performance tooling for mining and drilling companies. It also has a substantial presence in aftermarket parts and service, energy, mine de-watering, oil sands exploration, production drilling, and down-hole instrumentation. It provides underground coring and production drilling rigs and equipment.

Automated Underground LHDs

As discussed in the sub-section 'Autonomous Surface Mining Equipment' and at the beginning of this section, one of the largest hurdles to automating loading is replacing human judgement required for filling the bucket.

In the underground environment, In a collaboration between Queen's Mining Systems Laboratory (MSL) in Canada; Örebro University's Centre for Applied Autonomous Sensor Systems in Sweden; and Atlas Copco Rock Drill (Epiroc), also of Sweden, a new technology called auto-tunable robotic loading (ATRL) is being developed. ATRL allows automated LHD vehicles to 'feel' rather than 'see' the rock pile and make its adjustments accordingly.

Meanwhile, Sandvik has demonstrated [24] a fully automated LHD including a loading cycle. Sandvik has just launched its second LHD loader that can be automated which is now delivering an automated bucket filling assistant as a standard function with all Automine loading systems. The intelligent and self-adaptive LHD cycle in many applications delivers consistent bucket fill factors. The new Sandvik LH621i has a load capacity of 21 tons and is designed for rapid mine development and large-scale underground production and is a matching pair with the previously introduced Sandvik TH663i truck. The equipment has been designed automation ready, which makes the unit flexible, enabling Sandvik's AutoMine installation as a retrofit.

In May 2018, Epiroc released a number of automation features for its Scooptram underground loader. The Scooptram Automation regular package allows the Scooptram to be controlled through an operator station from a remote location. The automation package includes cameras, sensors and safety modules that are mounted onto the Scooptram as well as a safety system installed in the mine.

Figure 14: Caterpillar R1700G Underground LHD

Source: Caterpillar

Caterpillar has a significant position in the LHD market and offers semi-autonomous LHD operation. Its Cat Command for Underground automates the tramming and dumping component of an underground loader's load-haul-dump cycle. The operator has the ability to control the machine from an office or remote location away from the hazards of the underground mine. One or more machines can be controlled at once.

Joy (Komatsu) does not appear to offer any automated capabilities for its LHDs but does have automated control functions, such as return to dig and return to carry, to allow the operator to perform complex functions at a button press. The Joy 18HD and Joy 22HD (LHD) loaders also have an innovative SR hybrid drive technology which saves energy and costs; with faster acceleration leading to up to a 20% increase in tonnes moved and up to a 30% decrease in fuel consumption.

Underground Drilling Automation

The different cycles and operations of underground drilling are also at various stages of automation by OEMs. The most advanced automatic face drilling equipment already enables many underground mines and contractors to automate development drilling during shift changes, blasting and ventilation hours, allowing them to independently drill from one third to up to half a round, depending on the conditions at the face.

Despite the benefits that these drills provide, there are some limitations in terms of the number of holes that can be drilled in the absence of an operator. Limiting factors such as the life of the drill bit dictate how many holes can be drilled in certain rock conditions, thereby affecting production. Other instances which can negatively affect production include capability to drill perimeter holes reliably in an automated and unmanned process without excessive risk of wall collisions or the activation of the boom anti-collision system that can stop the boom movements and the production.

Sandvik's most advanced and productive automatic face drilling solutions are the intelligent Sandvik 400i series drills, DD422i and DD422iE and in January 2019 launched automation upgrades to these products. The upgrades include a new boom collision avoidance system, a new semi-automatic drill bit changer, and a Teleremote drilling control, which includes a drilling control panel that enables the drill to be operated remotely, including from the surface of the mine.

Figure 15: Simba M4 Underground Production Drill Rig

Source: Epiroc

In Sweden, the LKAB mine operates a fleet of Epiroc Simba long-hole rigs from one central control room, and there are similar systems installed in Finland and the USA.

Epiroc's face drilling rigs are used for blast hole drilling in underground mining and tunnelling. The rigs are equipped with up to four booms. It offers rigs with its Direct Control System (DCS) or with the computerised Rig Control System (RCS) to which different levels of automation may be added.

Joy (Komatsu) and Boart Longyear do not appear to offer any automated capabilities for their underground production drill rigs.

Minnovare [25], based in Australia, is an advanced technology company that specialises in improving the efficiency, productivity and overall profitability of industrial drilling operations, in both the mining and civil construction industries. Its Production Optimiser system combines advanced hardware and software that substantially improves drilling efficiency and productivity in underground mines. It reduces deviation, dilution and increases recovery. The Azimuth Aligner is used in mining exploration and civil construction projects to automate the drill-rig alignment process, substantially increasing accuracy and efficiency, whilst reducing downtime and costs.

Underground Autonomous Hauling

The development of autonomous hauling underground is far less advanced than developments on surface. This partly reflects the fact that it is a much smaller market, with a greater use of LHDs as well as the lower economies of scale to justify the higher capital costs.

In 2017, Sandvik launched the i-series truck family of Sandvik TH551i and Sandvik TH663i, and in 2018, launched the TH545i truck. These underground trucks are designed for intelligent mine operations and improved productivity. The trucks feature Sandvik's Intelligent Control System with data collection and reporting as standard. They come automation compatible and can be equipped with an optional AutoMine Trucking OnBoard Package.

Figure 16: Sandvik TH663i Underground Haul Truck

Source: Sandvik

Volvo has been testing a fully autonomous truck as part of a development project in the Kristineberg mine in Sweden. The self-driving truck is part of a development project aimed at improving the transport flow and safety in the mine. It appears that Joy (Komatsu) and Caterpillar do not yet offer any automated capabilities for its underground haulage trucks.

Electric Mining Equipment

Traditionally, both surface and underground mobile equipment in the mining sector have relied mainly on diesel engines which release emissions. There are already electric scoops in underground mines, a few with conventional batteries, but most units are tethered via an electric cable and so have limited range and other operating challenges. On surface electric trolley assist haul systems are sometimes used.

More recently, there has been an initiative to create battery operated equipment, driven by new developments in battery technology, as well as hybrid equipment with electric drive trains. This has made it possible to create powerful and productive equipment with lower or zero emissions, less noise and less heat. This also reduces the requirements for expensive ventilation and refrigeration systems.

Underground Battery Equipment

Epiroc introduced its first electric vehicles in 2016 (the Scooptram ST7) and at the end of 2018 announced second-generation products for the mining industry [26]. The range includes; 4 LHDs (3.6 to 18 tonne), a 42-ton truck, and a mid-sized drilling group including face drilling, production drilling, and rock reinforcement rigs. Epiroc is using ABB's optimised e-drivetrain on these vehicles. These vehicles have zero emissions, use 80% less energy, produce 80% less heat than conventional diesel LHDs. They can operate continuously with just two batteries and a ten-minute battery change.

Figure 17: Epiroc Minetruck MT42 Battery

Source: Epiroc

Also, in the underground environment, GE offers the Fairchild battery powered LHD, Artisan offers two battery electric LHDs and a 40-tonne haul truck, and RDH-Scharf offers a battery powered truck, three LHDs and a utility work platform.

Caterpillar's R1300G battery LHD is undergoing proof of concept trials in Canada. Sandvik is planning to introduce the Sandvik LH307B battery LHD which is also compatible with Sandvik mine automation and information management systems.

Byrncut, an international specialist underground mining contractor, engineering, and consulting group, is currently trialling an underground diesel-electric drive mine truck and suggests a 15-20% improvement in productivity.

Surface Battery and Electric Drive Equipment

Development of surface battery driven haul trucks is also taking place, albeit at a slower pace. Apart from the zero emissions, improved torque, and lower maintenance costs, these vehicles are also able to generate electricity through regenerative braking when travelling downhill.

In 2017, Lithium Storage GmbH and Kuhn Schweiz AG disassembled the Komatsu 605-7 and replaced the diesel engine with a synchronous electric motor capable of 590kW (800hp) of continuous power and up to 9,500 Nm torque and 700 kWh lithium-ion battery pack to power the electric motor. It has been renamed the eDumper. An important aspect has been the design of the battery to manage the heat emission and constructing it in such a way that a failing cell cannot affect neighbouring cells.

The Volvo Group's construction equipment subsidiary is working on electrifying several vehicles in its portfolio, especially for mining equipment. In August 2018 they deployed several new electric mining vehicle prototypes (trucks, loaders and excavators) for an emission-free quarry test.

Meanwhile, Safescape has developed the Bortana EV heavy duty electric utility vehicle [(27)]. The smart lithium-ion batteries have been purpose designed for mining, are maintenance-free, able to support rapid charging and achieve high energy density.

ETF Mining Equipment has a concept design for a large all-wheel-drive, battery driven haul truck that is modular in design, ranging from two pairs of wheels on each side to eight pairs of wheels on each side. The largest truck has 774 metric tonnes payload. Trucks of the same capacity can also operate together, connected as a haul train and driven by just one operator.

Figure 18: ETF D8-774 Mining Truck

Source: ETF Mining Equipment

OEMs are also introducing hybrid systems where a diesel engine powers an electric drive train. The hybrid system boosts available low speed torque and lowers fuel consumption and emissions. Siemens has developed an all-wheel-drive train with four motors for mining vehicles. This has been trialled on a BelAZ 75710 haul truck. The AC electric drive is powered by two 16-cylindar-diesel engines. At the end of 2018, Caterpillar announced more details on two new electric drive mining trucks to join its portfolio, the Cat 798 AC and Cat 796 AC. A Cat diesel engine drives the rear mounted generator. During retarding the wheel motors become generators.

Autonomous Rail Haulage Systems

We tend to think that rail automation is not new because there has been some form of automation on worldwide metro systems for many years. At the end of 2017, there were 55 fully automated metro lines in 37 cities around the world, consisting of automatic train protection, operation and supervision. However, one area where autonomous technology has yet to gain a foothold is rail freight. Trials are underway in Holland and Germany but implementing autonomous train-driving on a complex rail network, with passenger trains and freight trains, is more difficult than on a metro system. The one exception to this is in the mining sector where Rio Tinto has just completed commissioning of the world's first fully autonomous, long distance, heavy-haul rail network which is now in full operation.

As with most autonomous systems, the main benefits of an autonomous rail haulage system are productivity and safety because of the removal of the variability and potential errors caused through manual operation. Fully automated, driverless operations increase system availability, network capacity and operational efficiency. In the mining sector, both BHP and Rio Tinto have been trialling autonomous rail haulage systems at their iron ore mines in the Pilbara, Australia. Rio Tinto finally commissioned its first network of driverless trains in Western Australia at the end of 2018 after it completed its first long-haul journey with a completely autonomous locomotive in July 2018 [28]. The cost of its AutoHaul system is reported at A$940m.

Figure 19: Rio Tinto Fully Autonomous Rail Haulage

Source: Rio Tinto

Each of Rio Tinto’s fully autonomous trains, consists of three locomotives which haul 236 wagons carrying around 28kt of iron ore, and travel over 280km from Rio Tinto's mining operations to the port of Cape Lambert. The average journey cycle, including loading and dumping, is about 40 hours. Each locomotive has been installed with an onboard driver module which generates automatic reports on the exact position, speed and direction of travel of the entire fleet via IP communication to a central control centre in Perth, more than 1,500km away. The company's AutoHaul team has been trialling the technology and running thousands of hours of tests.

Getting to this point hasn't been straightforward for Rio Tinto and the actual commissioning of the autonomous trains project has been delayed a few times, partly due to software problems. The original target was to have a fully autonomous rail network in operation by 2016. Delays with the implementation of the autonomous trains hurt Rio Tinto's iron ore output in 2016. The company ended up producing 330Mt, down from the original target of 350Mt, as a result. Rio Tinto worked with Ansaldo STS (a Hitachi Group Company) to developed and deployed the AutoHaul train control system.

Neither BHP nor Fortescue Metals have switched to autonomous trains, but their rail automation programmes are under way. BHP began with a new 4G communications system and automated track signalling to reduce cancellations due to congestion.

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