Human Aspects of Automation and New Technology in Mining: Integrating People and Technology Through Human-Centred Design

A white paper prepared for ACARP project C34026

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Executive Summary

This white paper explores the potential benefits and failure modes associated with mining equipment automation and describes a framework for improving safety, health and productivity through human-centred design.

Autonomous trucks have been in use at surface mines for more than 10 years with demonstrable reductions in collision risks. Removing operators from drill rigs removes exposure to dust and vibration, access and egress risks, and safety risks associated with vehicle travel within the mine. Dozer automation has been less frequently employed, however removing the operator from the dozer cab has potential to eliminate exposure to hazardous areas such as stockpiles as well as exposure to whole-body vibration and musculoskeletal hazards. Automation of underground coal long walls has great potential to remove miners from a range of safety hazards, most notably rock falls, outbursts, or the ignition of methane; as well as health hazards such as exposure to respirable dust and noise. The safety and health benefits of removing operators from underground load-haul-dump vehicles is clear; including elimination of hazards including whole-body vibration, diesel particulate matter, and vehicle collision risks.

However, a range of credible failure modes introduced with automation were identified.

Software shortcomings	Communication technology disruption	Cyber security breach	Unauthorised access to autonomous zones
Loss of manual skills	Over-trust	Input errors	Inadvertent mode changes
Sensor limitations	Lack of system awareness of environment	Loss of situation awareness	Distributed situation awareness challenges
Complex interactions	Communication difficulties	Workload	Musculoskeletal injury risk factors

These failure modes all have human aspects. Current standards and guidance materials pay insufficient attention to the integration of humans and technology during the implementation of automation in mining.

Human systems integration incorporates human-centred analysis, design and evaluation within the broader systems engineering process. Human systems integration is a continuous process that should begin during the definition of requirements, continue during system design iterations, and throughout commissioning and operation to verify that performance, safety, and health goals have been achieved. A framework for human systems integration during implementation of new technology in mining is presented. Six domains relevant to mining are defined: staffing; personnel; training; human factors engineering; safety; and health.

Human systems integration processes adapted from other industries should be implemented during acquisition of automated mining equipment, and technology vendors should be required to provide a human systems integration plan.

Issues of particular importance include the design of interfaces to maintain situation awareness, the reduction of control room operator workloads, and the training of people who will undertake new roles. The extent of training required for all those impacted by the technology should not be under-estimated, and will likely be increased compared to previous roles. Ongoing training and competency assessment will be required as the systems are modified. Ensuring that sufficient numbers of trained control room staff are available to the industry is critical for both productivity and safety and health.

Introduction

The overall impact of increased mining equipment automation is likely to be improved safety and health. However, from an EMESRT control framework[1] point of view, introducing autonomous components creates new credible failure modes. While guidelines for the implementation of autonomous mining equipment exist[2], these existing documents pay insufficient attention to the integration of humans and technology.

This white paper explores the potential benefits and failure modes associated with mining equipment automation and describes a framework for improving safety, health and productivity through human-centred design

Based on publicly reported information, there were 183 installations of autonomous (and semi-autonomous) mining equipment fleets up to 2022 (Figure 1). Australian mines hosted 44% of the installations, with Canadian mines being the next most common venue (16%). The most common fleet types were autonomous surface haul trucks and semi-autonomous underground Load-Haul-Dump vehicles, followed by autonomous surface drill rigs. The majority of Australian installations were at surface mines (64%) while the majority of Canadian installations were at underground mines (62%).

The size of surface truck fleets are typically larger than other equipment types. The total number of autonomous haul trucks in operation globally in 2022 was 1070 (an annual increase of 39%), of which 706 were operated in Australia; and the number of autonomous trucks in operation globally is forecast to exceed 1800 by the end of 2025[3]. Mining equipment automation of most relevance to Australian coal mines are autonomous drilling, autonomous haulage, semi-autonomous dozers and semi-autonomous long walls. Underground loader automation will also be examined given the prevalence of this technology and the lessons that may be learned from it's implementation.

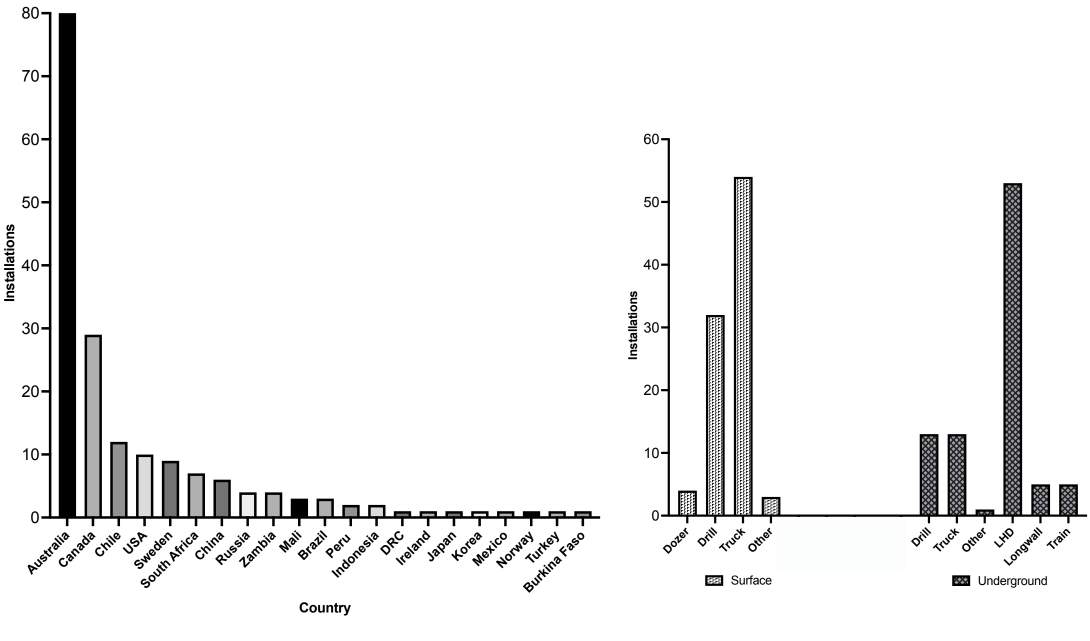

Figure 1: Installations of automated mining equipment fleets to 2022 by country and equipment type (N=183).

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1 https://emesrt.org/control-framework/

2 eg., Department of Mines and Petroleum (2015). *Safe mobile autonomous mining in Western Australia — Code of Practice*; ISO (2019). *Earth-moving machinery and mining — Autonomous and semi-autonomous machine system safety*; GMG (2019). *Guideline for the implementation of autonomous systems in mining;* NSW Resources Regulator (2020). *Autonomous mobile mining plant guideline.* DOC20/690069.

3 FutureBridge (2022). Autonomous Haulage Systems – The Future of Mining Operations. https://www.futurebridge.com/industry/perspectives-industrial-manufacturing/autonomous-haulage-systems-the-future-of-mining-operations/ (accessed May 24, 2023)

Automation benefits and failure modes

Autonomous Haul trucks

Autonomous haul trucks have been in use at surface mines for more than 10 years, providing significant cost savings and productivity benefits[4]. Safety has been an over-riding concern of both equipment manufacturers and mining companies, and the overall collision risk profile is markedly lower than manual truck operations. For example, an analysis of incidents associated with haul trucks, both manually operated and automated, recorded by BHP's Jimblebar mine in Western Australia for the four years that spanned the introduction of autonomous haulage to the site indicated that the overall incident rate declined by more than 90% over the period[5]. More recent information[6] indicates that the safety improvements at the site continued in subsequent years. Rio Tinto similarly have reported an order of magnitude difference in collision near-misses between autonomous and manual truck sites[7].

However, an analysis of "summaries for industry awareness" provided by the Western Australian Department of Mines, Industry Regulation and Safety[8] reveals general potential failure modes associated with automated mining equipment. Fifty-three summaries of incidents involving autonomous haul trucks reported between January 2010 and May 2021 were available.

Some of the incidents were unrelated to the autonomous functions of the truck. For example, an autonomous truck was struck by lightning:

> "An empty autonomous mining truck (AMT) was ascending a ramp at an open pit when it was struck by lightning. A nearby worker witnessed a tyre exploding and causing damage to the upper structure (including the deck, autonomy cabinet, engine and cab) of the AMT. … There were no injuries. Investigations found that the lightning strike initiated a chemical explosion that caused the uncontrolled deflation of the tyre."[9].

Although reported as a "potentially serious occurrence", the incident would perhaps be better characterised as a "potential serious incident avoided by automation", in that the consequences may well have been more serious if the lightning strike had occurred to a manual truck.

Mode error. In another case, an incident occurred as a consequence of a "check driver" inadvertently switching an autonomous truck into manual mode:

> "An autonomous mining truck travelling on the haul road in manual mode with a check driver in the cab, mounted a windrow. There were no injuries and the autonomous fleet were suspended. It appears that the check driver who was calibrating the truck inadvertently switched it into manual mode 15 seconds before the truck mounted the windrow"[10].

This is an example of the general category of a "mode error" failure that can occur with any system that may be operated in different modes.

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[4] Price, R., Cornelius, M., Burnside, L. & Miller, B. (2019). Mine Planning and Selection of Autonomous Trucks. In Topal, E. (eds) *Proceedings of the 28th International Symposium on Mine Planning and Equipment Selection*. Springer.

[5] Pascoe, T., McGough, S., & Jansz, J. (2022). From truck driver awareness to obstacle detection: A tiger never changes its stripes. *World Safety Journal, XXXI*(2), 15–28.

[6] Craig, B. (2022). Western Australia Iron Ore Update. Presentation & Speech. October 3, 2022. https://www.bhp.com/-/media/documents/media/reports-and-presentations/2022/221003_waiospeeches.pdf (accessed June 3, 2023).

[7] Fouche, L. (2023). Vehicle fatality elimination. Presentation to the Collision Avoidance Forum 2023. https://www.resourcesregulator.nsw.gov.au/sites/default/files/2023-03/Leon-Fouche-Rio-Tinto-Update-CA-Forum.pdf (accessed June 3, 2023).

[8] *Mining incident summaries*. https://www.dmp.wa.gov.au/Safety/What-accident-and-incident-19287.aspx

[9] Incident summary SA-067-26713, 06/01/2018

[10] Incident summary SA-MG-453-16969, 19/06/2014

Lack of system awareness of environment. A relatively common incident type represented in the incident summaries is loss of traction associated with wet roads. Ten incidents were described in the database, including:

> "While approaching the work area of an excavator, an autonomous truck lost traction and braked causing it to slide. The road had been recently watered by a water truck. After losing traction, the autonomous truck breached the lane, attempted to correct its path and maintained its position inside the lane for ~ 45 m. The body boundary then breached the lane again when a stop event was activated on the truck. Upon braking heavily, the truck slid ~ 20 m coming to rest ~ 4 m outside of its planned lane."[11]
>
> "An autonomous haulage system (AHS) truck was travelling unloaded down a 7 degree curved ramp in an open pit, at 47 km/h, when the rear wheels lost traction against the unsealed road surface. This caused the truck to initiate medium-braking. The truck slowed to 9 km/h, while remaining in its lane, before breaching its programmed path and causing a critical braking response. The truck then slid to the left-hand side and came to rest against a windrow. The total time travelled from the initial loss of traction to rest was 9 seconds and 4 seconds passed from critical braking to rest. An initial investigation indicates the ramp was overwatered. Engineering analysis of the data recovered from the truck showed that the truck operated as designed."[12]
>
> "An autonomous surface haul truck was travelling down the mine waste ramp at an open pit when it slid and rotated about 90 degrees before rolling onto the cab side. The incident was caused the truck moving from wet conditions on the ramp to dry as it slid."[13]

In each of these examples, although control of the autonomous truck was lost and the truck deviated from it's intended path (and in one case rolled onto it's side) no other vehicles were in the vicinity. It is also notable that while the trucks may have "operated as designed", the initiation of emergency braking while sliding may not have been the optimal response to the situation.

In two further examples, the loss of control resulted in a collision with another autonomous truck:

> "An empty autonomous haul truck (AHT) collided with a loaded AHT at an open pit. The empty AHT breached its lane and entered the path of the loaded AHT. Autonomous operations were suspended and an investigation commenced. It was raining heavily prior to the collision and the empty truck experienced a loss of traction."[14]
>
> "Following a rain event at an open pit, an autonomous haul truck made contact with the rear of another autonomous haul truck while on a pit ramp."[15]

In both cases, the vehicles involved were both autonomous and there was no risk of injury to persons. However, it is possible that more serious consequences would arise were an autonomous truck to lose traction whilst in the vicinity of an manual vehicle.

Communications failure. Another truck to truck collision occurred in February 2019. The incident summary reads:

> "An autonomous haul truck (AHT) at an open pit reversed and made contact with a parked AHT."[16]

Additional detail was provided in a news media report:

> "The reversing truck stopped when communications were severed. When the wi-fi coverage returned, the truck's LiDAR (light detection and ranging) technology kicked in, detecting the presence of the truck behind it and remained stationary.… However, the truck then reversed into the stationary machine".[17]

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[11] Incident summary SA-299-22131, 04/02/2016

[12] Incident summary SA-861-25701, 25/07/2017

[13] Incident summary SA-356-27825, 18/05/2018

[14] Incident summary SA-205-30271, 16/03/2019

[15] Incident summary SA-275-32600, 16/02/2020

[16] Incident summary SA-389-29984, 11/2/2019

[17] https://thewest.com.au/business/mining/fortescue-metals-group-auto-haul-truck-crash-christmas-creek-no-failure-of-system-ng-b881104957z

Although the Chief Executive Officer of the company is quoted as saying that the incident “was not the result of any failure of the autonomous system”, it appears that there was an failure of some kind involving a WiFi communications error between the truck and control room[18]. The consequences could have been serious if an occupied light vehicle had been located behind the truck at the time.

Loss of situation awareness. The most common type of incident described in the summaries involved interactions between an autonomous truck and another vehicle (eg., dozer, water cart, grader, service vehicle or light vehicle) in which the manually operated vehicle encroached into the permission line of the autonomous truck, causing the autonomous vehicle to brake. Eighteen such incidents were identified in the database, including seven in which the manually operated vehicle then collided with the autonomous truck.

One such incident was summarised as:

> “An automated haul truck (AHT) turned … into the path of a manually operated water cart. The AHT was commencing a loop to position itself beneath the excavator bucket. On realising the intended path of the AHT the water cart operator commenced evasive action. However, the two vehicles collided.”[19]

Further details of the incident were subsequently provided by the regulator[20] (Figure 2).

Summary of incident

Autonomous trucks were hauling mine waste on night shift at an open pit mine. The control room operator directed an autonomous haul truck to turn right at an intersection and perform a loop so it could be positioned under an excavator bucket on the pit floor. The intersection and turnaround loop existed in the control system but the intersection was not physically signposted or marked on the ground to alert manually operated vehicles.

A manned water cart was travelling in the opposite direction when the autonomous truck was about to turn to right. The water cart driver was not aware of the autonomous truck’s assigned path and, on recognising it, tried to take evasive action. The two vehicles collided, resulting in significant damage to the autonomous truck. The water cart driver received minor injuries.

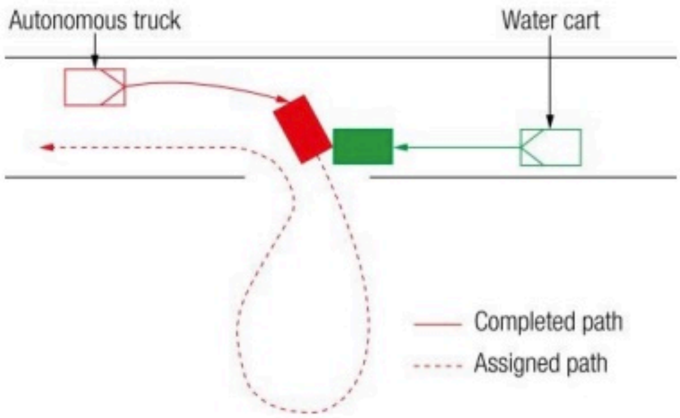

Figure 2: Description of the collision between a manned water cart and autonomous truck

[18] Bhattacharya, J. (2020). Wireless network capacity and capability is a pre-requirement for implementation of automation and other technologies in open-pit mining. *Journal of Mines, Metals and Fuels, 68*, 152–152

[19] Incident summary SA-605-17670, 16/8/2014

[20] https://www.dmp.wa.gov.au/Documents/Safety
MS_SIR_226_Collision_between_an_autonomous_haul_truck_and_manned_water_cart.pdf

The direct causes of the incident identified by the regulator were:

- "The travel paths of the autonomous truck and water cart intersected;
- The turnaround loop for the autonomous truck was released for use in the control system but the corresponding intersection was not delineated on the ground, nor its intended use communicated
- On detecting the water cart in its assigned path of travel, the autonomous truck's speed (about 40 km/hr) and response time meant it could not prevent the collision."

Contributory causes identified were:

- "The change management processes for planning and assigning roads in the control system were inadequate;
- *An awareness system was set up in the water cart to allow the driver to monitor the autonomous truck's path. However, at the time of the collision, the water cart driver was not fully aware of the intended path of the autonomous truck*." (emphasis added).

This last "contributory cause" identified hints at the failure mode — a loss of situation awareness by the water cart operator. The note also highlights the importance of the site awareness system provided in manually operated vehicles operated within autonomous zones.

Several other incident summaries also note the role of this interface. For example:

> "A collision happened between an autonomous truck and a water cart on a ramp in an open pit. The water cart operator drove onto an active haul road while wetting a section of the pit and *observed an autonomous truck on the screen.* The operator of the water cart determined that there was sufficient room to articulate with the truck approaching and continued in the direction of travel. As the water cart came into the vision of the autonomous truck, the truck applied the brakes and began to slow down. The truck wheels then locked up and contact was made between the two pieces of equipment. The vision of the autonomous truck was impaired as the truck was approaching from the offside of the water cart."[21] (emphasis added).

> "A water cart entered an intersection in the path of an autonomous haul truck during night shift at an open pit. The operator braked and came to a stop three metres from the truck. A light tower was facing the windscreen of the water cart impeding the operator's view of the intersection. *The operator used the mapping display to check on the location of autonomous vehicles and misinterpreted the location of the truck*."[22] (emphasis added).

> "As the driver of a light vehicle (LV) approached an intersection on a haul road he observed the flashing light and clearance light of an autonomous haul truck (AHT). *The driver of the LV looked at the screen to view the permission line of the AHT but was unable to view it and decided to zoom out on the screen.* At that point the LV driver saw the headlights of the AHT turn towards him as the two vehicles entered the intersection. The driver of the LV applied the brakes and stopped and the AHT's safety systems were activated to "exception" mode (where all brakes are applied) and the vehicle stopped. The two vehicles came to rest 5-10 m apart."[23] (emphasis added).

> "At a Y-intersection in an open pit a light vehicle (LV) avoidance boundary intersected the lane of an empty autonomous dump truck. The crossed path initiated a critical stop resulting in a near miss, with the vehicles coming to rest ~ 4.0 m apart. … *An investigation into the incident found that the LV driver lost situational awareness, having been distracted by focusing on the site awareness screen* located between the front seats of the vehicle out of the field of view of the driver.[24] (emphasis added).

These incidents highlight the importance of the site awareness system, and in particular the design of interfaces (Figure 3) provided to assist operators of manually operated equipment within the autonomous zone maintain situation awareness. In turn, this highlights the general importance of the design of interfaces intended to provide time-sensitive information to human operators.

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[21] Incident summary SA-992-22337, 05/03/2016

[22] Incident summary SA-019-30692, 03/06/2019

[23] Incident summary SA-380-18526, 15/01/2015

[24] Incident summary SA-039-18170, 08/12/2014

Figure 3: Site awareness interfaces provided within manual vehicles operated within autonomous zones at surface mine sites.

Over-trust. One of the "near-miss" collision incidents reported hints at a failure mode other than loss of situation awareness.

> "Replays … showed a potentially serious occurrence at an open pit mine. The AHT was approaching an intersection on a haul road near the ROM, and had its permission line out, indicating its intention to turn right. As it slowed down and started turning, a light vehicle approached from the opposite direction and continued entering the intersection. The AHT identified the collision risk, applied its brakes and came to a stop. The light vehicle did not stop, but continued through the intersection, passing less than 10 m from the AHT. The driver of the light vehicle failed to give way, as per pit permit requirements, and did not stop, call mayday or report the incident to their supervisor."[25]

It is hard to imagine the operator of a light vehicle failing to notice passing through an intersection less than 10m away from a haul truck. While this incident may have been a particularly egregious example of loss of situation awareness, it is more likely that this is an example of the general potential for "over trust" in automation to lead to behavioural changes that degrade the safety of the system — that is, the light vehicle operator had such trust that the autonomous truck would stop that they deliberately drove through the intersection in front of the truck. Combining this situation with a loss-of-traction event yields a plausible fatality scenario.

Complex interactions. Two final summaries of automation incidents deserve comment as examples of how unwanted outcomes can arise in complex systems in the absence of failure of any system component. The first resulted in a truck to truck collision:

> "An autonomous haul truck stopped on an open pit ramp. A single lane was created for other autonomous trucks to pass the truck. A worker arrived to manually recover the truck. It was started and driven up the ramp into the path of a second truck as it was passing. The trucks made contact, stopping on the ramp. … The proximity detection/site awareness system was not fully operational on the first truck when it travelled into the single passing lane."[26]

[25] Incident summary SA-520-26849, 09/01/2018

[26] Incident summary SA-051-28892, 03/10/2018

In this case, when the operator re-started the autonomous truck to drive it manually, there was a delay before the truck's site awareness system was actively broadcasting it's position. No feedback was provided to the driver that this was the case and the driver had no visibility of the autonomous truck approaching from behind. This combination of circumstances resulted in the autonomous truck being unable to stop when the manually operated truck was driven into it's path. All system components functioned as intended, however the collision still occurred.

Another incident resulted in an unusual interaction between two pedestrians and unexpected movement of two autonomous haul trucks that had serious potential consequences:

> "After two autonomous haul trucks (AHTs) at an open pit lost communication, two operators were tasked with relocating the vehicles. As the first driver entered the cab of an AHT, the vehicle moved forward while the operator applied the brake and switched to manual mode. As the second operator was about to board the other AHT, its horn sounded and the vehicle moved forwards, with the operator stepping out of the way."[27]

The regulator subsequently provided additional information[28] (Figure 4):

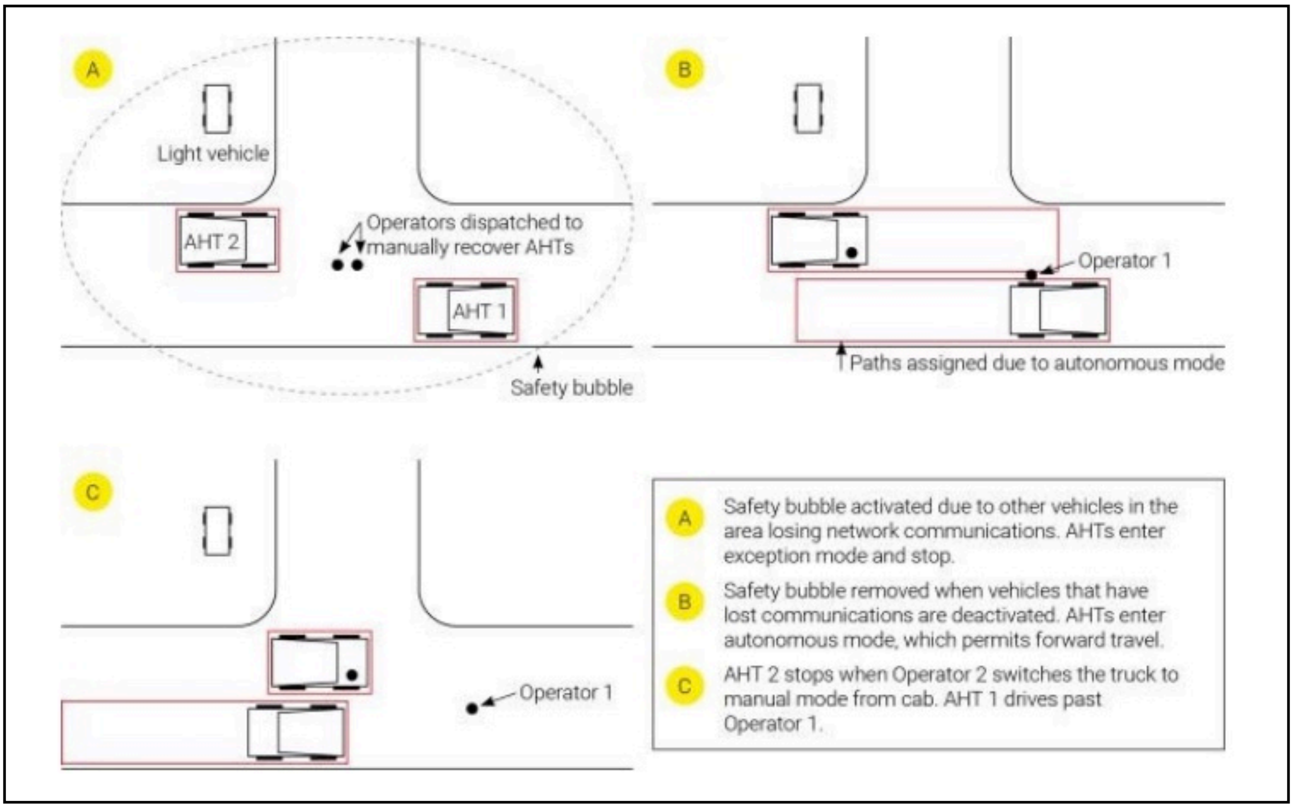

Figure 4: Description of unintended autonomous truck movements in proximity to pedestrians

The direct causes identified were:

> "Operators attempted to board the AHTs while they were not under their control
>
> The operators did not identify that the AHTs were in exception mode when attempting to board.
>
> Once the light vehicles in the area were deactivated, which removed the projected safety bubble, the AHTs reverted from exception to autonomous mode allowing them to resume operations."

Contributory causes were listed as:

> "AHTs were in exception mode and not suspended (unsafe mode to approach).
> Lack of understanding or clarity regarding the actions of the AHTs in various modes of operation.

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[27] Incident summary SA-743-32237, 29/12/2019

[28] https://www.dmp.wa.gov.au/Documents/Safety/MSH_SIR_286.pdf

Limited redundancy in communications network utilised by the AHS.
Ability for personnel to override system functions that are designed as critical safety controls.
Operators did not observe the AHTs status mode indicator lights.
Previous AHS communication issues may have desensitised the operators to potential hazards.
AHTs did not detect a person about to board."

Again, the loss of control of the situation occurred despite all systems functioning as designed. In both cases a lack of feedback to the people in the system about the state of the autonomous components, or a lack of understanding of the information provided, contributed to the event. These examples both illustrate why conventional failure-based risk analysis methods are insufficient to understand the risks associated with complex systems that include autonomous components. Additional analysis techniques such as Strategies Analysis for Enhancing Resilience (SAfER) and/or System-Theoretic Process Analysis (STPA) are also required.[29]

Input errors. In addition to the automated haul truck related incidents reported to the WA regulator, several other examples of incidents have been noted including:

> "Automation did not eliminate trucks from tipping on red lights. Mine Control were still required to remotely tip failed truck assignments. Therefore, controllers needed to observe the lighting system before overriding the truck."[30]

> "Although automation successfully prevented trucks from entering closed (Active Mining Areas), the system relied heavily on LV's to virtually lock the area. Driverless trucks drove into (Active Mining Areas) where light vehicles forgot to lock or engage the button effectively[31]

These incidents are both examples of errors during input to the system.

Software shortcomings. Another issue of concern is software change management. Considerable effort is required on behalf of mines to test the functioning of updates before installing updates because of the potential for software errors to be introduced. The extent of the effort is, in part at least, because of limited information provided by manufacturers to the mine sites about the software changes.

Control room situation awareness. The autonomous trucks and associated technology, and the people in both the control room and the field, form a joint cognitive system. Timely and appropriate decision making requires the joint cognitive system to maintain an accurate understanding of the state of the system and the environment to allow prediction of likely future events. No one person in the system has access to all the information required to maintain this situation awareness. Rather, the situation awareness is distributed across the system. Maintaining accurate distributed situation awareness is a dynamic and collaborative process requiring moment-to-moment interaction between team members and technology.

For example, the control room operator does not have direct access to information about roadway conditions and relies on people in the mine to provide the information required to allow appropriate decisions to be taken, such as slowing trucks to avoid loss-of-traction events. Similarly, the controller has access to system wide information that needs to be communicated to field roles. Communication between team members is clearly a critical aspect of maintaining accurate situation awareness, as is acquiring and interpreting information from autonomous system interfaces. Automated haulage control rooms were typically initially located at mine sites, however increasingly the controllers are being moved to remote operations centres which exacerbates this issue. The design of control room interfaces (eg., Figure 5) is crucial in allowing the control room operators to play their part in maintaining situation awareness.

Musculoskeletal injury risks. Some limitations in the design of the physical aspects of the controller workstations exist such as high monitor positions leading to head and neck extension and increased visual demands, although these can improved by the use of standing workstations (Figure 6). Input interface requirements also necessitate excessive pointing device use.

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[29] Hassall, M., Seligmann, B., Lynas, D., Haight, J., & Burgess-Limerick, R. (2022). Predicting human-system interaction risks associated with autonomous systems in mining. *Human Factors in Robots, Drones and Unmanned Systems, 57*, 78–85.

[30] Pascoe, T., McGough, S., & Jansz, J. (2022). From truck driver awareness to obstacle detection: A tiger never changes its stripes. *World Safety Journal, XXXI*(2), 15–28. p.20

[31] ibid

Figure 5: Autonomous haulage control room interfaces.

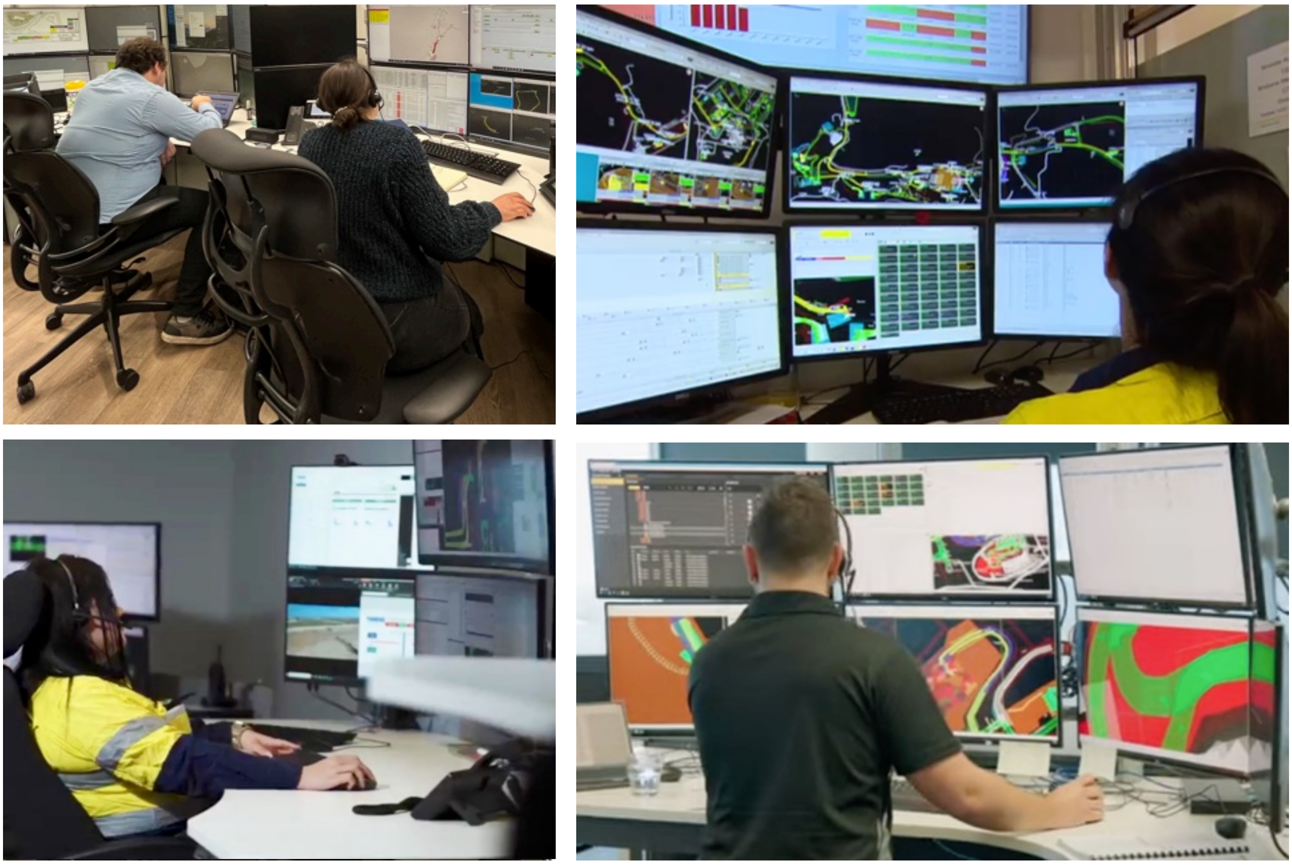

Figure 6: Automated haulage control workstations.

Workload. Control room roles involve high cognitive workload that may lead to performance decrements and/or adverse health effects. As well as the potential impacts on operator well-being and sub-optimal performance, there are implications for turn-over and subsequent recruitment and training costs.

For example, a controller interviewed by Pascoe explained that:

> "Previously for a manned operation you wouldn't, you have 40 trucks drivers that can think about it and do it yourself. You've got one controller, on average, looking after 25 trucks, with one builder. Planning all the work for those 25 trucks, as well. So, it's constant just churn; it doesn't stop; it's relentless…" [32]

[32] Pascoe, T. (2020). *An Evaluation of Driverless Haul Truck Incidents on a Mine Site: A Mixed Methodology.* Unpublished PhD thesis. Curtin University of Technology. p. 157.

The workload is unpredictable, and this also increases stress. As Pascoe et al noted:

> "Supervisors can be completing monitoring tasks and simultaneously be confronted with network outages, truck slides and broken-down machines"[33]

Interruptions to work were also noted by operators as a source of stress, for example, routine site access requests interrupting building work that requires sustained concentration.

Chirgwin similarly noted high autonomous controller workload across multiple control rooms:

> "Several controllers that had experience in manned and autonomous operations had assumed that automation would make their work life easier, but the experience was the opposite and their workload, cognitive load and communication responsibilities had increased because of automation"[34]

and observed that the workload is also increased by allocation of additional, perhaps unnecessary, tasks:

> "… many organisations continued to hold on to outdated ways of working, and … continued to add tasks to the controller role. An example of this is the insistence of manual reporting. Despite the fleet systems having the ability to capture multitudes of data, all of the controllers interviewed reported that they were required to manually report on what was occurring during their shift and justifications for their actions. This task was largely seen as a task given to the controller with the aim of saving someone else time …"[35]

Communication difficulties. Controller workload is also increased by the extent of communication required with people in field roles. The requirement for the control room to monitor and respond to multiple communication channels (radio, telephone, in-person) creates potential for frustration, interpersonal conflict, and cognitive overload. The multiple communication channels means that the field staff do not know if the control room operator is already attending to another information source. They may also not appreciate the time required to action a request before the next request can be attended to. Interpersonal group dynamics are important in this situation, particularly rapport between control room operators and field staff where interactions are largely virtual, and particularly if the controller has limited previous field experience.

The rapid expansion of autonomous haulage has resulted in mining companies encountering considerable difficulties attracting, training, and retaining controllers. This has become a vicious cycle, in that the scarcity of controllers results in high workloads, leading to burn out which exacerbates the issue. Chirgwin described the situation she observed in multiple control rooms:

> "…controllers were often observed being on-shift before mining production employees, and were often the last to leave, going beyond their allocated 12hr shift. It was not uncommon to see a controller not take a break (including a toilet break) for up to 6h, and sometimes that extended to the entire shift. … Often there was no-one to replace the controller for their break, so they would either not have one, or the other controllers or their supervisor would take on the additional workload for that break period."[36]

The shortage of controllers leads to difficulty releasing staff for training that, in turn, also contributes to increased stress and reduced job satisfaction.

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33 Pascoe, T., McGough, S., & Jansz, J. (2022). Haul Truck Automation: Beyond Reductionism to Avoid Seeing Turtles as Rifles . *World Safety Journal, XXXI*(3), 26–38. p. 33.

34 Chirgwin, P. (2021). Skills development and training of future workers in mining automation control rooms. *Computers in Human Behavior Reports*, *4*, 100115. p. 7.

35 ibid

36 ibid

Blast-hole drills

Removing operators from drill rigs removes exposure to dust and vibration, access and egress risks, and safety risks associated with vehicle travel within the mine. The advantages were described by one operation as follows:

> "From our point of view in operations, what we are looking for is the precision of the process, which in drilling still depends a lot on the human factor. But before this depended on an operator in the cabin who is exposed to risk – they are often close to the highwall, or close to bench edges or ore faces. So to remove the operator from the cabin and put them in the IROC actually improves the utilisation of the fleet while also improving the quality of life of the operator – no exposure to noise, vibration or climate extremes like cold. But it is also more efficient – for example at site the operator has a one hour lunch break, but in addition to that time they come out of the cabin, travel for maybe 30 minutes to the canteen and then the same back again. So there is unavoidable underutilisation of the drill asset. Here, the autonomous drill operator still has a lunch break but eliminates all that site related extra time … Plus the machine continues to drill anyway during lunch breaks and shift changes."[37]

A 37% increase in drilling rate and improved accuracy; as well as increased availability was reported for a different mine[38].

Several incidents associated with autonomous drill rigs were reported in the WA incident summaries. In two cases the rig collided with a windrow or trough; in three cases a collision, or near collision, occurred with another drill rig; and in one case the autonomous drill rig collided with a light vehicle. Where contact between vehicles occurred, the cause of the failure of the drill rig's obstacle avoidance system were not explained. For example:

> "At an open pit, an autonomous mobile drilling rig was proceeding to a new drill pattern location. During the journey, the machine made contact with a parked light vehicle (LV). The drill was stopped and a supervisor informed. No injuries were sustained. The remainder of the autonomous fleet was made inactive while hazard detection systems were tested for effectiveness. An investigation was commenced."[39]

While drill rigs are slow moving and hence the probability of a high consequence collision is low, the incident summaries highlight that obstacle avoidance technologies are fallible.

Input errors. In another case, an input error in the location of the autonomous boundary was noted as a cause of the incident, ie:

> "An autonomous drill boundary at an open pit was updated to allow an autonomous drill to be relocated to another area of the drill pattern. While relocating, the autonomous drill crossed the cone-delineated boundary into a manned drill area. Workers in the vicinity saw the autonomous drill behind a manned drill and called the control room operator to stop the autonomous drill tramming. It stopped about 15 metres from the manned drill. The supervisor was notified and both drills stopped work. There were no injuries and an investigation was commenced. *It was found that the updated autonomous drill boundary was incorrect*." (emphasis added).[40]

This is an example of error during input to the control system which is a general category of potential errors associated with the introduction of autonomous components.

Different approaches to the design of autonomous drill rig workstations have been taken to allow both teleoperate and autonomous control. In some cases, the physical controls of the drill rig have been replicated in a control room. For example, the workstation illustrated in Figure 7 is used to control three automated drill rigs. Other approaches are illustrated in Figure 8, where joysticks are provided but abstracted from a drill cab context.

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[37] Moore, P. (2023). Anglo American Los Bronces – inside the IROC. *International Mining*. https://im-mining.com/2023/08/22/anglo-american-los-bronces-inside-the-iroc/ (accessed August 23, 2023).

[38] Ellis, Z. (2023). Autonomous surface drilling: KGHM Robinson mine. *Presentation to the Mine Automation and Emerging Technologies Health and Safety Partnership meeting*, September 21, 2023.

[39] Incident summary SA-762-28966, 9/10/2018

[40] Incident summary SA-554-27908, 27/5/2018

Figure 7: Replica drill cab workstation and interface for automated drill rig. (Westrac, 2022).

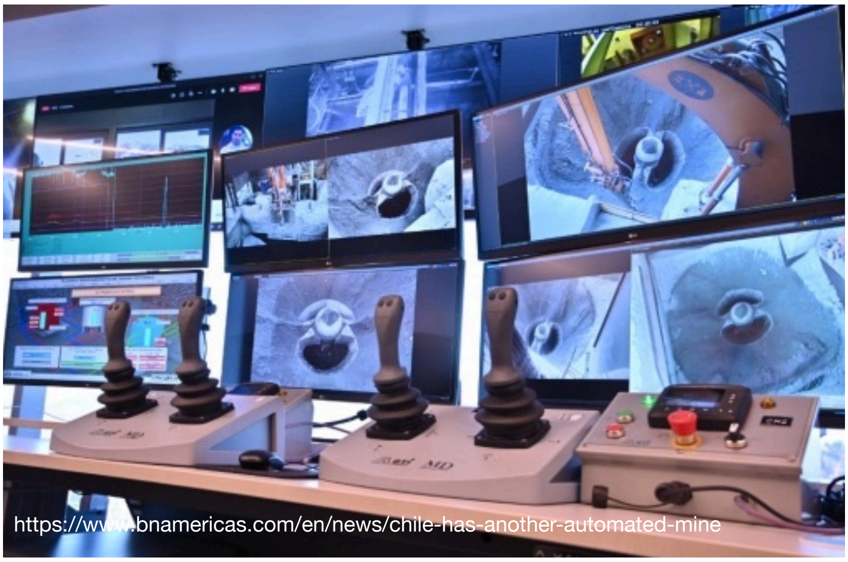


Figure 8: Joystick controls for automated drill rigs.

Another approach is illustrated in Figure 9. Multiple video camera feeds provided a 360 degree view from the drill rig, and from a remote viewpoint, assisting the remote operator maintain global and local situation awareness. The visual interfaces previously provided within the drill cab are replicated, however the controls located within the manual cab have been replaced by a wireless Xbox controller. The controls on the wireless Xbox controller cause different actions in each of three modes of operation (drill mode, setup mode and propel mode). This creates the potential for mode errors. The probability of mode errors may be reduced by ensuring that the current mode of the machine is readily apparent to remote operators. For example, auditory feedback may provide a means of identifying machine mode that does not rely on visual attention.

Operating a control in a direction which causes an effect opposite in direction to that intended is another potential error mechanism. The probability is reduced by ensuring directional control-response compatibility. Determining the appropriate directional control-response relationship is complicated in this situation because the orientation of the wireless remote control may vary during use, however there does seem to be a potential inconsistency in the directions chosen for “hoist”, “jack up” in drill mode, “swing deck up” in set up mode (all upwards when the remote is in the orientation illustrated in Figure 10); and the control directions illustrated for “mast up” in the setup mode (the reverse).

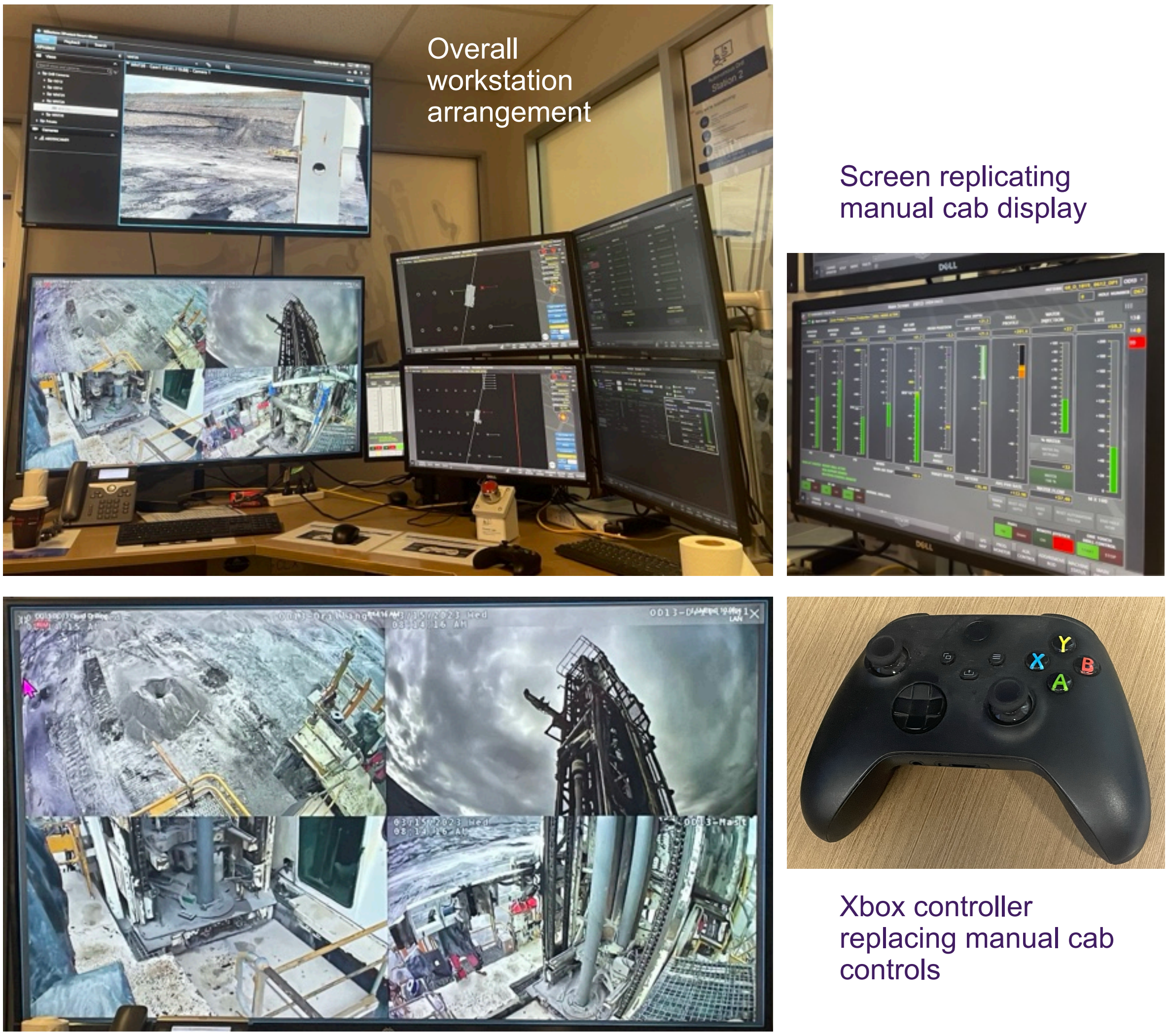
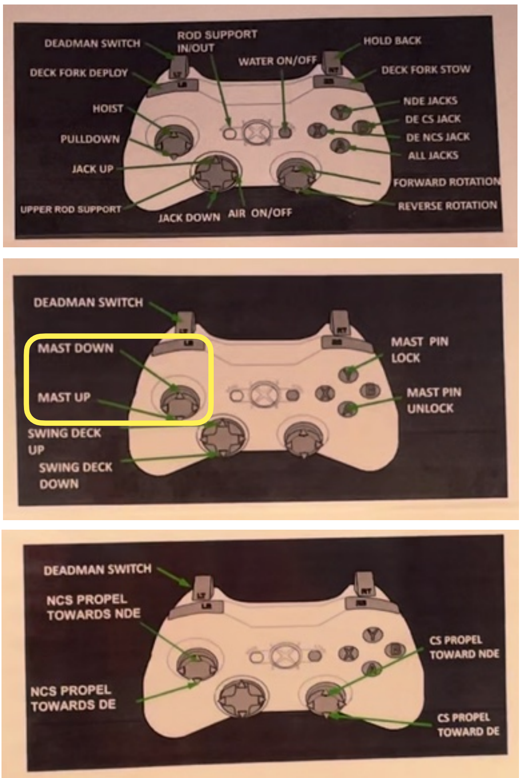


Figure 9: Autonomous blast-hole drill workstation and interfaces



Drill Mode

Setup Mode

Propel Mode

Figure 10: Remote-control drill functions in different modes

Dozers

Dozer automation has developed following the use of non-line-of-site remote control operation that was undertaken to remove human operators from hazardous areas such as stockpiles. Removing the operator from the dozer cab also eliminates exposure to whole-body vibration and musculoskeletal hazards, however the potential for loss of situation awareness is created because of the loss of direct perceptual cues.

Video displays and a range of additional interfaces are provided to maintain situation awareness in both remote control and automated modes of operation. An extended evaluation of different combinations of visual, auditory and motion cues for dozer teleoperation was undertaken as part of ACARP project C20021[41]. Figure 11 illustrates the interface provided for these trials that incorporates machine instrument information and schematic information. The intended use-case was bulk dozer push at surface coal mines. Visual quality was found to be the dominant factor influencing performance while the provision of motion cues provided no additional performance benefit.

Figure 11: Interfaces provided for remote dozer interface experiments (Dudley, 2014)

A current semi-automated dozer workstation is illustrated in Figure 12. Here the interfaces provided include both plan and elevation views of dozer position in addition to video feeds to aid the operator maintain situation awareness. In this case, one operator remotely supervises up to four dozers. Safety and health benefits include eliminating exposure to whole body vibration and other musculoskeletal risk factors, access and egress, and site transport risks.

The transition to semi-autonomous dozer operation required extensive operator training, starting with two dozers and gradually working up to four. Utilisation has been increased 25% and productivity is enhanced by software that automates decision making. Alterations to the production schedule were required to take advantage of the increased equipment availability[42].

[41] Dudley, J. J. (2014). *Enhancing awareness to support teleoperation of a bulldozer.* MPhil Thesis, School of Mechanical and Mining Engineering, The University of Queensland.

[42] Gleeson, D. (2021). Thiess hits new heights with SATS dozer technology at Lake Vermont. International Mining. https://im-mining.com/2021/06/02/thiess-hits-new-heights-sats-dozer-technology-lake-vermont/ (accessed August 9, 2023)

Figure 12: Semi-automated dozer interfaces.

Loss of situation awareness. A collision between an semi-automated dozer and an excavator occurred in 2019. The NSW Resources Regulator has provided an investigation report[43]. Semi-autonomous (SATS) dozers were being utilised to undertake bulk push operations. This technique requires an excavator to clean the rear bench material where the dozers reverse to before commencing a push. The material is used to create a windrow across the back of the dozer push area. A procedural control was in place in that a manually operated machine should not operate in the active dozer slot.

Three semi-autonomous dozers were being supervised from the remote operator station by a trainee operator under instruction. Each dozer is fitted with four video cameras and these video feeds are displayed at the operator workstation (Figure 12). The workstation includes teleoperation controls. In semi-autonomous mode, the operator allocates a dozer to a slot and conducts the first push of the mission via teleoperation mode. The dozer then continues to operate in the same slot autonomously until either the mission is completed or until 12 passes have been conducted and the operator must reconnect with the dozer.

According to the investigation report:

> "At 1.30pm, the excavator operator resumed work within the SATS avoidance zone from the north, travelling towards the south. As the edge bund was constructed using material from the highwall face, some loose material was hanging up across the face. The operator used the excavator to scale the loose material from the face, as he travelled towards the southern section of the SATS avoidance zone.

[43] NSW Resources Regulator (2019). *Collision between semi-autonomous dozer and an excavator*. DOC19/758086.

As the excavator had previously scaled and cleaned up the northern area, a windrow had been built between the rear bench and the SATS dozer push slots. This resulted in the excavator working between the highwall face and the windrow. As loose material was scaled down, it was added to the windrow. The task progressed towards the south until the excavator travelled to the end of the windrow and was positioned adjacent to the rear of slot 16.

At this point, dozer DZ2003 was operating in slot 16, while dozer DZ2002 and dozer DZ2010 were working in adjacent slots in the southern section of the avoidance zone about 50 metres away. Dozer DZ2003 had been operating semi-autonomously for some time. Immediately before the collision, the SATS operator had selected and was observing dozer DZ2002 until dozer DZ2010 ceased pushing. The SATS operator switched to this machine and started fault finding.

Dozer DZ2003 had completed a push and was reversing towards the rear of slot 16 to start the next push. At this time the excavator proceeded past the windrow, into slot 16. About 1.40pm, dozer DZ2003 hit the rear of the excavator. When initial contact was made, the excavator was pushed about 1.5 metres sideways, into the base of the highwall. The excavator then stopped sliding and dozer DZ2003 continued to tram in reverse, colliding with the excavator multiple times trying to reach its programmed GPS coordinates.

Dozer DZ2003 eventually lost traction and after five seconds, the control system faulted and stopped tramming. From the initial contact to dozer DZ2003 stopping was about 14 seconds. The excavator had some damage however the operator was uninjured."[44]

When a dozer is selected by the supervisor, a screen in front of the operator displays the four cameras corresponding to the dozer that is the focus of the operator's attention. A small side panel also shows two camera views for each of the other three dozers. Figure 13 illustrates the supervisor's view immediately prior to a collision. While information was available to the supervisor, it was not provided in a way that facilitated maintenance of accurate situation awareness. Humans are very poor at vigilance tasks. It is entirely understandable that the impending collision was not identified by the supervisor who was focussed on fault finding on a different dozer.

Figure 13: Remote operator station provided to the supervisor of three semi-autonomous dozers (A - top left); video images available (B - bottom) immediately prior to the collision between dozer 2003 and an excavator (C - top right).

44 ibid

Longwalls

Working at the longwall of an underground coal mine is associated with a range of safety hazards, most notably rock falls, outbursts, or the ignition of methane. Health hazards, and particularly exposure to respirable dust and noise, are also associated with working in the area.

Automation has great potential to reduce the exposure of miners to these hazards. Current technology has removed two miners to a surface control room. While the majority of the crew remain underground, they work in less hazardous locations. Remote guidance technology continuously steers the longwall, automatically plotting its position in three dimensions and allowing real-time monitoring of progress. Control room interfaces (Figure 13) provide video feeds and other information to compensate for the loss of direct perceptual information. According to the CSIRO, longwall automation technology has increased productivity by 5–10 per cent through improved consistency[45].

Credible failure modes associated with longwall automation include: loss of situation awareness resulting from the of loss of direct perception including vibration of machine and auditory information from cutting heads; loss of manual skill; communication technology disruptions; communication difficulties; high cognitive workload; and musculoskeletal injury risks associated with sedentary work.

Rather than relocating some crew members permanently from underground to the control room, the miners rotate between the surface and underground on different shifts. This is beneficial in rotating exposure to the physically sedentary but cognitively demanding control room work across miners as well as maintaining underground knowledge and skills. While decreasing safety and health risks, further automation will reduce these rotation opportunities.

Although the control room interfaces (Figure: 14) provide extensive information sources and appears well designed, it was noted by operators that additional cameras views would be beneficial and that communication between the surface control room and underground workers at the longwall was difficult at times.

Figure 14: Automated longwall control room and interface

[45] https://www.csiro.au/en/work-with-us/industries/mining-resources/mining/longwall-automation

Load-Haul-Dump vehicles

Semi-automated Load-Haul-Dump vehicles (LHD) have been installed at more than 50 mines globally since 2006. Operators located in a control room load the LHD bucket using via tele-operated control. The loader is then switched to autonomous mode to travel to the dump where the load is dumped autonomously. The loader then autonomously returns to the next load point selected by the operator. Operators may be responsible for supervising multiple loaders. A range of interfaces are provided to allow the remote operator to maintain situation awareness and remotely control the loading phase (Figure 15).

Figure 15: Semi-autonomous underground LHD operator interfaces.

The safety and health benefits of removing miners from these underground vehicles is clear. Exposure to musculoskeletal hazards including whole-body vibration are eliminated, as are vehicle collision risks, and head injuries associated with LHD buckets catching the rib while tramming. A 16-20% reduction in exposure to diesel particulate matter has been estimated to be associated with the introduction of automation to underground copper mines[46].

[46] Moreau, K., Lamanen, C., Bose, R., Shang, H., & Scott, J.A. (2021). Environmental impact improvements due to introducing automation into underground copper mines. *International Journal of Mining Science and Technology, 31*, 1159-1167.

Unauthorised access to autonomous zones. No reports of injuries associated with autonomous loaders have been identified. This is likely to be, in part at least, because current practice is to isolate all other equipment and pedestrians from the zones in which autonomous LHDs operate. However, incidents have occurred where automated equipment has been activated in an isolated autonomous area with multiple working faces while persons were located at another face[47].

Remote-control loaded buckets, or average, contain smaller loads than manually loaded buckets. However, overall productivity is higher because increased equipment utilisation arises as a consequence of being able to continue operation through blasting and shift changes. LHD supervisors located remotely from the loaders may not feel the quality of the roadway and allow the loaders to drive at speeds that increase unplanned maintenance requirements.

The location of the control workstation for the semi-autonomous LHDs varies across sites. Some sites locate the LHD control room underground and this was seen as beneficial for maintaining communication with other staff underground. Other sites have chosen to locate the LHD control room on the surface of the mine to reduce underground travel time, or in a remote operations centre in a city location at some distance from the mine. At one mine, semi-autonomous LHD supervision is undertaken both in a control room on the surface of the remote mine and in a control room located in the company's city office. This additional location allows staff who are unable to undertake a Fly-In-Fly-Out roster to continue to work for the mine.

The integration of semi-autonomous loaders into existing production systems is not straight forward and sites noted that difficulties typically arise in maintaining production during the transition. Not every site that implemented semi-autonomous LHDs has persisted with the technology and some sites have taken several attempts before being successful. Implementation of LHD automation requires a strong mandate from the highest levels of the company to be successful in the face of inevitable, if temporary, production declines during the implementation phase.

This observation is consistent with the findings of a case-study of the successful implementation of semi-autonomous loaders at CMOC NorthParkes. The strategies for successful automation implementation included: involving all people who will be impacted; encouraging constant communication between operators and designers; provide operators with essential information; avoid providing non-essential information; provide the operators with flexibility; empower operators to take action; and taking advantage of the new possibilities provided by automation[48].

One issue identified at NorthParkes during the initial preparation for the transition to autonomous LHDs was that all underground tasks would be affected by the change. For example, at shift change the continued operation of LHDs from the surface enables production to continue, removing time pressure and allowing greater time for shift handover. However, it was also identified that access to, or through, sections of the mine where autonomous loading was in operation would be prevented and this impacted on the performance of many other tasks.

Constant communication between operators and designers throughout the implementation and subsequent operation of the semi-autonomous loaders was critical in developing and refining the control room user interface. Continuous presence of manufacturer expertise on-site allowed a rapid feedback loop with designers.

Providing operators with opportunities to suggest modifications to the system was a key feature in the success of the implementation. Operators continually updated a list of issues, and a 'wish list' of improvements, which were fed back to the system designers, and many changes resulted. For example, equipment damage was occurring because the loader was hitting the walls of the draw point while under manual control. Using the laser scanners already in place for autonomous navigation to detect the proximity of the walls was suggested during manual operation and to convey this information to the operators through changes in colour of the scanning information provided on the teleoperation assist window. This information was also used to automatically apply the brakes if necessary to prevent collision with the walls.

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47 Thompson, J. (2023). Hecla Greens Creek case study. https://www.cdc.gov/niosh/mining/features 2023automationpartnershipmeeting.html

48 Burgess-Limerick, R., Horberry, T., Cronin, J., & Steiner, L. (2017). Mining automation human-systems integration: A Case study of success at CMOC-Northparkes. Proceedings of the 13th AusIMM Underground Operators' Conference 2017, pp 93-98. Melbourne: AusIMM.

Similarly, wheel spin caused damage to the LHD wheels but was hard for operators to detect while loading remotely. A wheel-slip detection sensor was added and an indication of wheel slip provided to the operator through a change in colour of the schematic loader wheels in the teleoperation assist window. In both cases the presentation of relevant information to the operators in a meaningful way ensured the information could be used effectively to reduce equipment damage.

Relevant information is also conveyed inadvertently, rather than by design. One operator explained that it can be difficult to gauge when the bucket has been lowered sufficiently to the ground in preparation for loading, however if too much pressure is placed on the ground by the bucket, the front wheels will raise and the wheels slip. The operator noted that the camera shake which could be seen on the video feed when the bucket was lowered was a useful cue.

Conversely, another change made during system implementation was to reduce the number of fault alarms presented to the operator. Many of these alarms, while relevant to an engineer during commissioning, were not relevant to the day-to-day operation of the LHD. As well as being a nuisance to operators because each message required acknowledgement, becoming habituated to frequent non-essential error messages was reported to have led on at least one occasion to an operator failing to react to a critical error, with potentially serious consequences.

Providing flexibility in information provision was another strategy employed. The LHDs are fitted with a microphone and the audio is available to the operators, however it was found that this information was not wanted by the operators and the audio is left off because the nuisance value of the noise outweighed the benefit of any relevant information conveyed.

Many details of the automation implementation were left to production crews to determine. For example, in the transition to autonomous loading, some crews decided that crew members would be trained for autonomous control, while other crews chose to have specialist autonomous operators. The number of LHDs for which an operator should have responsibility was also determined by the crews. While four loaders can be controlled by one person, the cognitive load was overly fatiguing and three was determined to be optimal. During operation, some crews choose to allocate three LHDs to be controlled by each operator, while other crews allowed more flexibility, with all loaders able to be controlled by any of the three operators on shift at any one time.

Allowing crews to choose different strategies provides opportunity to evaluate different options, and comparisons between operator and crew productivity can be used to fine-tune operator strategies and identify aspects of operator behaviour which lead to improved productivity. Production crews have also taken action without involving the system designers. One issue encountered was that the cameras and scanners were accumulating dust which was causing the automation to fail. While the system designers were exploring options for on-board cleaning mechanisms, the crews devised a means of dumping water on the camera and scanners when required. Making all aspects of the control system as flexible as possible and giving operators maximum control over the automation increases the opportunities that operators have to adapt to new situations.

The implementation of autonomous loading has also had unanticipated consequences for future process improvements. The ability to more flexibly execute different draw point extraction patterns, and modify these extraction patterns, prompted the development of optimisation software to determine in real-time the optimal pattern of extraction. This is itself a form of automation which will provide assistance to the shift-boss in maintaining situation awareness of the extraction and aid decision-making.

Credible failure modes

The introduction of automated components introduces new failure modes that have potential for adverse safety and health outcomes including:

- *Software shortcomings.* It is difficult to verifying that software is trustworthy. Testing can only reveal the presence of flaws rather than prove the absence of errors. This is particularly true if machine learning is involved. Operations that have implemented autonomous machinery described spending considerable time verifying the operation of software updates prior to release.
- *Communication technology disruption.* Autonomous mining systems are dependent on continuous digital communications. Considerable effort is required to ensure the required networks are in place and maintained. Loss of network connectivity is a common cause of lost productivity and at least one potentially serious incident has occurred in which a communication interruption was implicated.
- *Cyber security breach.* Breaches have occurred and this is an risk that will increase. Continuous attention to network security is warranted given the potential damage that a malicious actor could achieve. The human aspects of cyber security also require attention.
- *Unauthorised access to autonomous zones*. Incidents have occurred at surface mines where vehicles not fitted with site awareness systems have accessed active autonomous zones without an escort. In the underground context, incidents have occurred in which automated equipment was activated in an isolated autonomous area with multiple faces while persons were located in the area.
- *Loss of manual skill.* Machine operators' manual skills will deteriorate if not practiced. Whether this is a concern will depend on whether the system concept of operation includes reinstating manual operation at any time, and in what circumstances.
- *Over-trust.* People working in the vicinity of autonomous systems are likely to change their behaviour to take advantage of the perceived safety features of the system. Driving a light vehicle through an intersection in front of an autonomous truck, trusting that the truck will take evasive action, is an example. Ensuring that people working with autonomous components have an accurate understanding of the system's capabilities and limitations, and the physical constraints, is important. So is supervision, monitoring, and enforcement of safety related procedures such as hierarchy road rules.
- *Input errors.* Whenever human controllers are responsible for entering information into the system there is potential for error. The probability of such errors is reduced by effective software and interface design. Where remote control is included in the concept of operations the design of the workstation controls should take into account the possibility of mode errors, and ensure that directional control-response compatibility is maintained.
- *Inadvertent mode changes.* Whenever equipment can be operated in different modes there is potential for inadvertently switching between modes. This includes switching between autonomous and manual modes.
- *Complex interactions.* Systems including including autonomous components may give rise to unpredicted adverse consequences even when all components function as intended. The use of systems-based risk analysis techniques such as STPA is recommended to identify and control such potential outcomes.
- *Sensor limitations.* Sensors have limitations that can result in the system losing awareness of the situation. These limitations require analysis and management.
- *Lack of system awareness of environment.* Removing operators from direct perceptual contact with the operating environment creates the potential for loss of awareness of the environment. One example is wet roadways leading to loss of traction.
- *Loss of situation awareness.* Several incidents have occurred in which the operators of equipment being operated manually in the vicinity of autonomous haulage have failed to predict the movements of the autonomous haulage, despite being provided with a system interface intended to provide this information. Incidents have also occurred in which an unfolding situation has not been identified by a control room operator despite, for example, video feeds providing the necessary information. These incidents highlight the difference between information being available and being perceived, and hence the critical importance of interface design to assist the people within the systems to understand current system states and accurately predict the likelihood of future states.

- *Distributed situation awareness challenges*. A related issue is that, in many systems, there will be no individual who possesses all the information required to maintain overall situation awareness of the whole system. Instead, the situation awareness is distributed across the people and technology within the system. Maintaining accurate distributed situation awareness is a dynamic and collaborative process requiring moment-to-moment interaction between team members and technology that can be hindered by limitations in system, or interface, design.
- *Communication difficulties.* Communication between team members is critical. Difficulties associated with technology limitations, or cognitive overload caused by multiple simultaneous communication channels, can impede performance with potential safety or health consequences. Non-technical skills, and the absence of psychosocial hazards, are also required to ensure effective team-work.
- *Workload.* Potential exists for control room operators or others impacted by the introduction of automation to be overloaded, with consequential risks of errors, and adverse health consequences. The workload of all people within the system is a key aspect for consideration in system design.
- *Musculoskeletal injury risk factors.* Long duration sedentary work with few breaks combined with static or awkward postures and/or excessive pointing device use, especially if accompanied by psychosocial risk factors such as high cognitive workload, time pressure, and/or conflict with peers or supervisors may create a situation in which musculoskeletal injury risk is high.

Effective risk management requires analysis of these potential unwanted events during system design. The analyses undertaken should include task-based risk assessments involving a range of operators and others effected by the system, and systems-based techniques, in addition to conventional hazard based risk analysis techniques. All of these failure modes involve human interactions with the technology. The risks should be reduced during human-centred system design that focusses on the role, capabilities, and limitations of the people in the system. Residual risks need to be understood by mine management to allow effective controls to be devised, implemented, and monitored.

Human-systems integration

Human-systems integration (HSI) refers to a set of systems engineering processes originally developed by the Defence industry to ensure that human-related issues are adequately considered during system planning, design, development, and evaluation[49].

For example, the USA Department of Defence[50] requires program managers to undertake a combination of risk management, engineering, analysis, and human-centred design activities including:

- the development of a human-systems integration management plan
- taking a human engineering design approach for operators and maintainers
- task analyses
- analysis of human error
- human modelling and simulation
- usability and other user testing
- risk management throughout the design life-cycle
- developing a training strategy

And obliges lead systems engineers to:

> "use a human-centered design approach for system definition, design, development, test, and evaluation to optimize human-system performance … Conduct frequent and iterative end user validation of features and usability … (and) … ensure human systems integration risks are identified and managed throughout the program's life-cycle…"[51]

The processes described aim to ensure that human considerations are integrated into the system acquisition process. The importance of including human systems integration subject matter experts throughout the acquisition program is made explicit. It is notable that, in contrast to the mining automation guidance, system safety is considered to be a domain within human systems integration.

Similarly, the USA National Aeronautics and Space Agency requires human systems integration to be implemented and documented in a Human Systems Integration Plan. The plan identifies the steps and metrics to be used throughout a project life-cycle, and the methods to be undertake to ensure effective implementation. Effective application of human systems integration is understood to result in improved safety and health, increased user satisfaction and trust, increased ease of use, and reduced training time; all leading to higher productivity and effectiveness.

The methods have progressively diffused to civilian industry. For example, the USA Federal Railroad Administration[52] defines HSI as a "systematic, organisation-wide approach to implementing new technologies and modernising existing systems." It combines methods, techniques and tools designed to emphasise the central role and importance of end-users in organisational processes or technologies. Useful HSI guidance has been provided for the acquisition of complex railroad technologies[53].

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49 International Council on Systems Engineering (2015). *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. Wiley.

50 USA Department of Defense (2022b). *Instruction 5000.95. Human Systems Integration in Defense Acquisition*. p. 6.

51 USA Department of Defense (2020). *Instruction 5000.88 Engineering Defense Systems.* p. 23.

52 USA Federal Railroad Administration. *Human Systems Integration*. https://railroads.dot.gov/human-factors/elearning-attention/human-systems-integration

53 Melnik, G., Roth, E., Multer, J., Safar, H., & Isaacs, M. (2018). *An Acquisition Approach to Adopting human Systems Integration in the Railroad Industry*. US DOT. DOT/FRA/ORD-18/05.

HSI for mining system acquisition

Human systems integration incorporates human-centred analysis, design and evaluation within the broader systems engineering process. That is, human systems integration is a continuous process that should begin during the definition of requirements, continue during system design iterations, and throughout commissioning and operation to verify that performance, safety, and health goals have been achieved.

A framework for human systems integration during implementation of new technology in mining is presented in Figure 15[54]. Six domains relevant to mining are defined: staffing; personnel; training; human factors engineering; safety; and health.

"*Staffing*" concerns decisions regarding the number, and characteristics, of the roles that will be required to operate and maintain the joint human-automation system. Decisions here may well require consideration of the outcomes of investigations in other domains particularly where workload issues are involved.

The "*personnel*" and "*training*" domains concern, respectively, the related issues of the characteristics of the personnel who will be selected to fill those roles; and the extent and methods of training, and competency assessment, involved in preparing personnel to obtain and maintain competencies (knowledge, skills, and abilities) required for safe and effective operation and maintenance of the joint human-automation system. Rather than decreased, training requirements for operators interacting with highly autonomous systems are likely to be increased to ensure the operation of the automation is fully understood. For example, automated system controllers need to understand: system hazards and logic, and reasons behind safety-critical procedures; potential results of overriding controls; and how to interpret feedback. Skills for solving problems and dealing with unanticipated events are also required. Emergency procedures must be over-learned and frequently practiced.

Instructional system design models[55] exemplify the application of human factors principles to training. In essence, such models involve front-end analysis steps (analysis of the situation, task, equipment interface, trainees, training needs, and resources, leading to definition of the training functional specifications), followed by design and development steps (training concept generation, training system development and prototyping, and usability testing) and system evaluation steps (determining training evaluation criteria, collection and analysis of these data, and subsequent modification of the training if indicated).

The front-end analysis (or training needs analysis) step in training design is critical. In particular, a comprehensive analysis of the tasks performed by equipment operators and maintainers is required before the training needs and associated functional specifications can be determined. The aim of the task analysis is to describe the knowledge, skills, and behaviours required for successful task performance, and identify the potential sources and consequences of human error. This task analysis would typically involve interviews with experts, reviews of written operating and maintenance procedures, and observations of equipment in use. It should include consideration of the information required by equipment operators and maintainers and how this information is obtained, the decision-making and problem-solving steps involved, the action sequences, and attentional requirements of the task. The task analysis should be conducted systematically, and well documented, to provide a solid foundation for the design of training and to provide a template for future training needs analyses.

An extension of the task analysis to include a cognitive task analysis may be justified for more complex task–equipment interfaces. Cognitive task analysis seeks to understand the cognitive processing and requirements of task performance, typically through the use of verbal protocols and structured interviews with experts. The outcomes of a cognitive task analysis include identification of the information used during complex decision making, as well as the nature of the decision making. The cognitive task analysis can also reveal information which will underpin the design of training and assessment. Again, the outcome of a cognitive task analysis may include identification of design deficiencies which should be fed back into the design process.

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54 Burgess-Limerick, R. (2020). Human-systems integration for the safe implementation of automation. *Mining, Metallurgy & Exploration*, *37*, 1799-1806.

55 Gordon, S.E. (1994). *Systematic Training Program Design: Maximising Effectiveness and Minimizing Liability*. Englewood Cliffs, NJ: Prentice Hall.

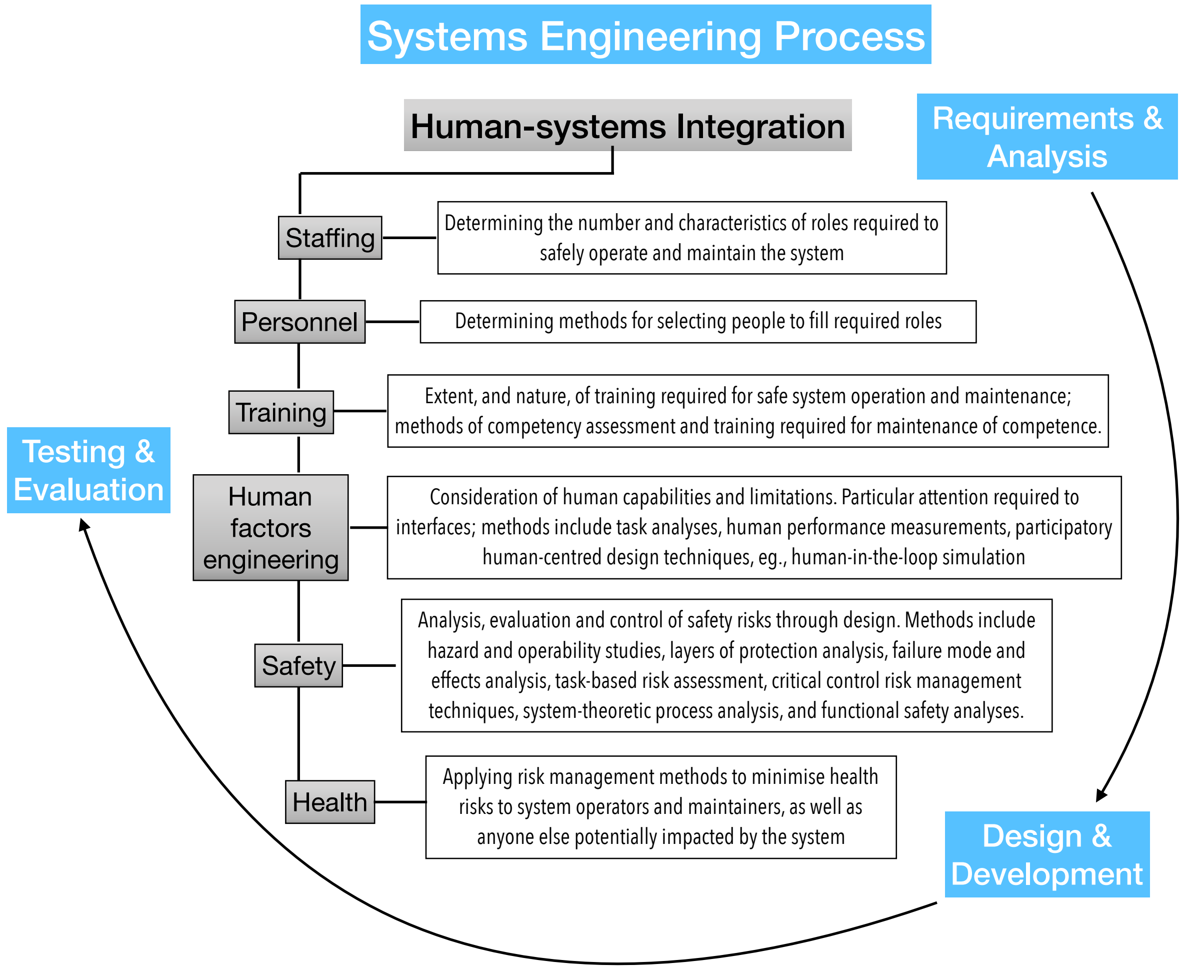

Figure 15: Human systems integration for mining automation.

The results of the task analysis are also used in the second phase of training design to define the actual contents of the training program, as well as the instructional strategy required. Regardless of the content of the training (the competencies required), or the methods employed, most effective instructional strategies embody four basic principles:

1. The presentation of the concepts to be learned
2. Demonstration of the knowledge, skills, and behaviours required
3. Opportunities to practise
4. Feedback during and after practise[56]

An initial training design concept is typically refined iteratively through usability evaluation of prototype training models, until a fully functional final prototype is considered ready for full-scale development. Issues to be considered include the introduction of variation and the nature and scheduling of feedback. A compelling case has been presented[57] to suggest that variation in the way tasks are ordered and in the versions of the tasks to be practised is important, and that less frequent feedback should be provided. Whilst immediate performance may be reduced, retention and generalisation are enhanced as a consequence of the deeper information processing required during practise.

Evaluation of the consequences of training is also an essential and non-trivial step, and the task analysis aids in determining the appropriate performance measures to be used in evaluation (or competency assessment). A valid training evaluation requires careful selection of evaluation criteria

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[56] Salas, E., & Cannon-Bowers, J. (2001). The science of training: A decade of progress. *Annual Reviews of Psychology, 52*, 471–499.

[57] Schmidt, R.A., & Bjork, R.A. (1992). New conceptualizations of practice: Common principles in three paradigms suggest new concepts for training. *Psychological Science, 3*, 207–217.

and measures (closely connected to the task analysis results) and systematic collection and analysis of data. The use of simulation is a promising method for allowing trainees to be exposed to rare events, as well as for competency assessment.

"*Human-factors engineering*" encompasses the consideration of human capabilities and limitations in system design, development, and evaluation[58]. In the automation and technology context, this is particularly important in the design of interfaces between people and automated components. While the use of human engineering standards (eg., MIL-STD-1472H) may be useful, they are not sufficient. Prescriptive standards are often too general to be helpful in specific situations, they do not address tradeoffs that may be necessary, and they reflect the technology of the time at which they were written.

Other methods employed in human factors engineering include task analyses such as those described in the previous section, and human performance measures (e.g., workload, usability, situation awareness), as well as participatory human-centred design techniques[59]. Human-in-the-loop simulation allows analysis of the activities undertaken to achieve tasks during the design phase[60].

ISO 9241 provides principles for human-centred design of computer-based interactive systems which will be relevant to many automation projects:

" a) The design is based on an explicit understanding of users, tasks and environments

b) users are involved throughout design and development

c) the design is driven and refined by user-centred evaluation

d) the process is iterative

e) the design addresses the whole user experience

f) the design team includes multidisciplinary skills and perspectives". [61]

Use-cases, that is, a description of a task performed by a person interacting with a system and the system responsibilities in accomplishing that task[62] provide a starting point for user interface design.

The "*safety*" domain includes consideration of safety risks such as those identified in ISO 17757. Relevant methods include traditional risk analysis and evaluation techniques such as hazard and operability studies, layers of protection analysis, failure modes and effects analysis, as well as functional safety analyses, and systems-theoretic process analysis (STPA).

STPA in particular may be useful for analysis of complex systems involving automated components because both software and human operators are included in the analysis[63]. STPA is a proactive analysis method that identifies potential unsafe conditions during development and avoids the simplistic linear causality assumptions inherent in traditional techniques. Safety is treated as a control problem rather than a failure prevention problem. Unsafe conditions are viewed as a consequence of complex dynamic processes that may operate concurrently. STPA also includes consideration of the wider, dynamic, organisational context in which the automated system is situated. STPA has been successfully used during the development of automated bulldozers[64] and automated haulage[65]. Other systems-based analysis techniques (eg., SAfER) may also be useful[66]

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[58] Horberry, T., Burgess-Limerick, R., & Steiner, L. (2011). Human factors for the design, operation and maintenance of mining equipment. Boca Raton: CRC Press.

[59] Horberry, T., Burgess-Limerick, R & Steiner, L. (2018). *Human-Centered Design for Mining Equipment and New Technology*. Boca Raton: CRC Press.

[60] International Council on Systems Engineering (2023). *Human Systems Integration: A Primer. Volume 1*. INCOSE.

[61] International Standards Organisation (2010). Ergonomics of human-system interaction Part 210: Human-centred design for interactive systems. ISO9241-210. p. 9.

[62] Constantine, L.L. & Lockwood, L.A.D. (2001) *Structure and Style in Use Cases for User Interface Design*. In M. van Harmelen (ed.), Object-Modeling and User Interface Design. Addison-Wesley.

[63] Leveson, N.G. & Thomas, J.P. (2018). *STPA handbook*. MIT.

[64] Beasley, P. & McAree, R. (2020) *SATS Automated Mission Planning*. ACARP project C27063, Current projects report, February 2020.

[65] Baillio, B. (2020). *ASI Experience with STPA.* Unpublished document, ASI Mining.

[66] Hassall, M. E., Sanderson, P. P., and Cameron, I. T. (2014). The development and testing of SAfER: a resilience-based human factors method. *Journal of Cognitive Engineering and Decision Making, 8,* 162-186.

The "*occupational health*" domain encompasses the use of risk management techniques, and task-based risk assessment in particular[67], to ensure that the system design minimises risks of adverse health consequences to system operators and maintainers, and indeed, anyone else potentially impacted by the system activities. These analyses should encompass all operational and maintenance activities associated with the autonomous component or system.

One health issue associated with the introduction of autonomous systems to mining is the potential impact on the physical and mental health of control-room operators tasked with interacting with autonomous systems. Stress associated with high (or low) cognitive workloads, potentially combined with reduced social interactions and low control of workload, and/or production pressures, may lead to adverse mental health consequences.

An overall focus on human systems integration includes consideration of interactions and potential trade-offs between decisions made in different domains. For example, decisions regarding automation and interface complexity may influence personnel characteristics and training requirements, as well as the anticipated number of people required for system operation and maintenance; while issues highlighted during the safety analysis may well lead to additional human factors engineering work to reduce risks.

[67] Burgess-Limerick, R., Joy, J., Cooke, T. & Horberry. T (2012). EDEEP - An innovative process for improving the safety of mining equipment. *Minerals*, *2*, 272-282.

Implementation of HSI

Guidance provided for the rail industry[68] has been adapted in the following section for the acquisition of new mining technologies. Although the stages of systems engineering are presented sequentially, the reality is that iterative loops occur both within stages and between stages. While the results of evaluations conducted during design and development will certainly influence subsequent design iterations, they may also feedback to changes to requirements, or even result in changes to the concept of operations.

Analysis

The initial stage of the systems engineering process is analysis. Human-centred analysis activities conducted as part of human systems integration address the following:

- Concept of operation — What are the goals of the system, and in particular, what are the anticipated operational and maintenance roles that people will play? Who will these people be? What knowledge and skills will they have? What diversity is anticipated? Are there other people inside or outside the system that should be considered?
- Contexts — What is the range of operational contexts and use cases? Are there different modes of operation? What range of environmental conditions is anticipated?
- Tasks — how will functions be allocated within the system? What physical tasks will people need to perform? What monitoring or decision-making tasks need to be undertaken? What current tasks will no longer be undertaken or altered? What are the critical tasks that are performed by people? A variety of task analysis techniques may employed depending the nature of the tasks. Similarly, analyses of workload and situation awareness are likely to be appropriate.
- Known challenges / lessons learned — Are there known human performance concerns based on experiences with similar systems in the same or other industries? What can be learned from previous incidents or near-misses?
- Safety & health — What hazards may be present? How could adverse safety or health outcomes occur? What errors could people make and what would be the consequences? How can the potential for detection of both human and technological errors, and recovery from errors, be increased? What critical controls are required to prevent or mitigate adverse safety or health outcomes?
- Tradeoffs — Are there tradeoffs between human systems integration domains that need to be evaluated? Are there tradeoffs between the human systems integration domains and other systems engineering elements (e.g., cost) that require examination?

Requirements

The output of these analyses leads to human systems integration requirements that inform subsequent system design and development. Potential requirements include:

- Information — What information needs to be received by people in the system to maintain situation awareness? How should the information be presented to best support decision making?
- Control — What controls and modes of interaction with the system are required?
- Communication — What communication channels are required inside and outside the system? What methods of communication should be provided?
- Physical environment — What physical workstation designs are required, eg., layout, lighting, visibility, reachability? How will human diversity be accommodated?
- Selection and Training — How will the people in the system be selected? What training (initial and ongoing) will be required? How should the training be undertaken? How will competency be assessed and reassessed?

68 Melnik, G., Roth, E., Multer, J., Safar, H., & Isaacs, M. (2018). An Acquisition Approach to Adopting human Systems Integration in the Railroad Industry. US DOT. DOT/FRA/ORD-18/05.

Design

Based the explicit understanding of users, tasks and environments, a human-centred design and development process involving users is undertaken by a multidisciplinary team including human factors expertise. The process is iterative, likely involving the design and testing of prototypes of increasing fidelity, and likely to involve human-in-the-loop simulation.

Design and development outcomes will include:

- Work environment — Design of physical environments to maximise performance, as well as health and safety. Human engineering standards may be particularly relevant to physical design.
- Software and interfaces — Design of the overall software architecture, as well as the interfaces through which information is received by humans, and through which input is given by humans, to ensure efficient and safe performance under normal and abnormal conditions.
- Training — Design of the curriculum, training methods, and competency assessments.
- Documentation — Developing readable, understandable, and usable procedures, training manuals and related operations and maintenance documentation that reflect "work-as-done" rather than "work-as-imagined".

Testing and evaluation

User-centred evaluation occurs throughout the entire systems engineering process, as well as at final system validation. Testing and evaluation activities include:

- Planning — Human systems integration issues should be incorporated into the overall systems engineering testing and evaluation program.
- Evaluation of prototypes — Users representing the diversity of the intended workforce participate in evaluations of prototypes of increasing fidelity. Both physical and virtual simulations may be useful, human-in-the-loop simulation even more so.
- Human engineering discrepancy resolution — Aspects of the design that do not meet requirements during the iterative evaluations are systematically identified and tracked. Corrective actions are proposed and implemented.
- Final validation — Each requirement requires evaluation in the final system validation. Evaluation scenarios include the contexts and use cases identified during the analysis stage. Data collected will include process measures (eg., workload and situation awareness) and outcome measures, as well as user evaluations.

Human-systems integration program plan

During the preparation of proposals to implement any new technology at mines, and particularly if automated components are involved, vendors should be required to submit an human systems integration program plan that details the human systems integration work that will be performed in collaboration with the purchaser; how it will be done; and by whom.

A human-systems integration program plan should include:

- Overview — An overview of the proposed system; preliminary concept of operations, associated human roles, and operational environment; experiences with predecessor systems.
- Organisational capabilities — Summary job descriptions and the qualifications of key human-systems integration practitioners within the vendor.
- Program Risks — A discussion of how human-systems integration risks will be identified and addressed.
- Human systems integration activities — The specific human systems integration activities that will be performed by the vendor in collaboration with the purchaser to address each of the domains of human systems integration during system analysis, design, and evaluation. Identification of who will undertake these activities.
- Human systems integration schedule — A milestone chart identifying each human systems integration activity, including key decision points, and their relationship to the program milestones.

Conclusions

While the introduction of automated mining equipment has great potential to reduce safety and health risks, new credible failure modes are introduced. The new failure modes all have human aspects. Current standards and guidance materials pay insufficient attention to the integration of humans and technology during the implementation of automation in mining.

Human systems integration processes adapted from other industries should be implemented during acquisition of automated mining equipment, and technology vendors should be required to provide a human systems integration plan.

Issues of particular importance include the design of interfaces to maintain situation awareness, the reduction of control room operator workloads, and the training of people who will undertake new roles. The extent of training required for all those impacted by the technology should not be under-estimated, and will likely be increased compared to previous roles. Ongoing training and competency assessment will be required as the systems are modified. Ensuring that sufficient numbers of trained control room staff are available to the industry is critical for both productivity and safety and health.

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