Mine of the Future: Disruptive Technologies that Impact our Future Mine Worker Health & Safety Research Focus

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Executive Summary

The mining industry is undergoing significant changes as mining companies are looking to gain a competitive advantage by adopting smart mine technologies to decrease costs and increase efficiency. Smart mine technologies include technologies associated with automation and robotics, wireless communications, smart sensors, wearable platforms, augmentation of reality, interconnectivity of devices and data analytics. Surface iron ore mines in Western Australia are moving rapidly to adopt smart mine technologies, and appear to be the closest mines to achieving completely autonomous mining. In the US, the adoption of smart mine technologies has been much slower, but interest is now growing in metal mining in particular. There are a number of companies that offer smart mine technologies to the mining industry.

The introduction of smart mine technologies into mining will potentially affect worker health and safety. NIOSH needs to be positioned to both proactively address worker health and safety issues associated with smart mine technologies, as well as leverage those same technologies to improve miner health and safety. Since US mining companies are only now incrementally implementing smart mine technologies, the timing is right for the development of a roadmap laying out the role of NIOSH to prevent injuries and health hazard exposures that may develop.

To that end, a workgroup was formed to develop a research roadmap for NIOSH that includes a vision statement and research focus areas. The vision statement that the group drafted is: Proactively address worker health and safety associated with disruptive mine technologies. Six research focus areas that describe the scope of research that NIOSH should engage in to address emerging mine worker health and safety issues related to the adoption of disruptive technologies in the mining industry have been identified. These six research areas provide a roadmap as well as a tool for making strategic decisions for capacity building and resource allocation for future mine worker health and safely research at NIOSH. They are: Situational Awareness, Automation, Data Analytics, Human Factors, Sensors, and System Safety. A brief definition of each research focus area is as follows:

- **Situational Awareness:** The perception of elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future.
- **Automation:** The process by which a piece of equipment operates automatically, usually under some level of computer control. Automation can have various levels, including: semi-autonomous (some human intervention needed) and fully autonomous.
- **Data Analytics:** The process of extracting information from raw data using specialized statistical computer systems to discover patterns and meaning.

- **Human Factors:** The systematic application of relevant human characteristics, abilities, expectations, and behaviors to the design and operation of tools, machines, procedures, and facilities.

- **Sensors:** Devices that respond to a physical stimulus (such as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control). Smart sensors process the sensor data before passing it on.

- **System Safety:** The application of engineering & management principles, criteria and techniques to achieve acceptable risk, within the constraints of operational effectiveness, time and cost throughout all phases of the system life cycle.

Each research focus area has been developed to include health and safety implications, the NIOSH comparative advantage, expected outcomes and risks, competencies required, and facilities needed to address any health and safety issues. Lastly, recommendations are provided for NIOSH to move toward proactively addressing worker health and safety issues that arise related to smart mine technologies. The top priority recommendations are:

- Partner with mining companies that have plans to implement automation and smart mine technologies;
- Participate on standards committees to address safety standards for mining automation technology;
- Partner with local universities and research organizations performing automation and smart mine technology research;
- Collaborate with the NIOSH Center for Occupational Robotics Research, and the NIOSH Center for Motor Vehicle Safety on occupational health and safety issues that are common in other industry sectors;
- Develop staff in focus areas Situational Awareness and Human Factors in the context of automation.

1.0 Vision Statement

Proactively address worker health & safety associated with disruptive mine technologies.

2.0 Introduction

Surface and underground mining traditionally have been highly mechanized using machinery controlled by people to cut, load, transport, and haul commodities. For the most part, the equipment and processes have largely been incrementally improved over the years. However, this is beginning to change with the advent of smart mines that use the disruptive technologies associated with automation, robotics, wireless communications, smart sensors, wearable platforms, augmentation of reality, interconnectivity afforded by the Internet of things (IoT) technologies, and data analytics. These technologies are resulting in a dramatic transformation from a traditional mine to an innovative smart mine that is critical for reducing production costs, increasing mining efficiencies, and improving safety. The full text of this and other industry trends can be found on the BMI Research website at http://www.bmiresearch.com/articles/smart-mining-the-key-areas-of-innovation. Already, the smart mining market has generated a revenue of $5,328 million in 2014 and is projected to reach $15,800 million by 2022 with a compound annual growth rate of 14.9% (PR Newswire, 2017). Mine automation plays a key role in the smart mine where current and near-term applications include (Cosbey et al, 2016):

- Autonomous haul trucks and loaders
- Semi-autonomous crushers, rock breakers and shovel swings
- Automated drilling and tunnel-boring systems
- Automated long-wall plough and shearers
- Geographic information systems (GIS) and Global Positioning Systems (GPS)
- Autonomous equipment monitoring
- Offsite control rooms

With smart mine technologies, production costs may decrease and mining efficiencies may increase by improving the flow of traffic in the mine, optimizing energy and fuel consumption, reducing unscheduled maintenance, reducing damage to machines and machine abuse, and by reducing interruptions to the mining operation from weather and human needs. The more smart mine technologies are used, the less the variability in the mining process.

In addition to productivity, smart mine technologies could also provide improved worker health and safety by relocating workers to a safer and healthier environment. Operator exposure to noise, dust, vibration, inclement weather, and slips, trips and falls from climbing on and off equipment may be effectively reduced. Autonomous vehicles also may reduce employee fatigue-related incidents from extended shifts, shift work, and demanding work associated with operating heavy equipment. However, safety issues can be introduced with smart mine technologies. For instance, significant incidents have occurred involving autonomous mobile equipment in Australia and other countries as follows (DPM, 2014):

Incidents:

- An autonomous haul truck reversing over a waste dump
- A water truck colliding with an autonomous truck at an intersection
- A blast hole autonomous drill rig reversing into the rear of a stationary blast hole drill rig
- A grader colliding with an autonomous truck
- An autonomous truck backing over an edge

Contributing factors:

- Specification and design of safety systems
  - Detection systems not included in design
  - Detection systems only monitoring forward motion

    - Users remotely overriding safety systems

- Human Factors Issues
    - Failure to respond appropriately to system information or warnings
    - Misinterpretation of system information or ignoring warnings
    - Lack of system knowledge and understanding of how the autonomous equipment system works
    - Not adhering to personnel or equipment exclusion zones
- Process Issues
    - Personnel in active areas without having appropriate communication devices
    - Visual inspections, verification and audits failing to identify deviations
    - Information not displayed or readable

Although smart mine technologies may bring efficiency and worker health and safety advantages to a mining operation, there has not been extensive adoption in the United States as compared to Australia. For instance (see Table 1 below, and Appendix A), US implementation of smart mine technologies is primarily found in parts of longwall operations and semi-autonomous LHDs. In Australia, complete mining operations have been automated at surface mines.

While autonomous vehicle operation is becoming more prevalent and is anticipated to grow into the foreseeable future, Brian Fox, Vice President, Marketing-Automation within Atlas Copco's Mining and Rock Excavation Business Area, said one of the reasons mining hasn't been as quick to adopt automation as industries such as manufacturing is because of the ever-changing geological and environmental conditions in which the machines work. Additionally, there has not been a large demand from customers. However, the industry has now reached a point where smart mine technologies will be necessary in order to remain competitive and to achieve further health and safety improvements (Cullen and Fox, 2016).

Brendon Cullen, ControlMaster Product Manager at RCT, notes that one of the constraints associated with integrating autonomous control within mining is the interaction of machinery and personnel on existing sites. "Some functions of the mining process still need human control and will for the foreseeable future." Justifying the cost and ensuring the reliability of autonomous technology have also been factors hindering more widespread adoption (Cullen and Fox, 2016).

2.1 State of Smart Mine Technologies in Mining

Today, the approach for smart mining is to incrementally introduce new technologies rather than trying to transition from a traditional mine to a fully smart mine. This approach is pragmatic given the capital expenditures needed and given the numerous complexities and interactions among smart mine technologies (Norton, 2017).

The technologies being adopted in mining (Table 1) varies by mining industry sector (coal, metal, nonmetal, stone, sand and gravel), by type of mining (surface or underground), and by location of the mining company in the world. Another factor is size of operation, with smaller mining operations being less likely to implement advanced technologies because of the initial cost. In Western Australia, there are several mining companies that have surface iron ore mining operations that appear to be moving quickly toward completely autonomous mining, and they are probably the most advanced, technology-wise mining operations in the world.

Table 1- Mines implementing Smart Mine Technologies.

Country	Company	Ore Mined	Surface/Underground	Technology
AUSTRALIA	BHP Billiton	Iron Ore	Surface	Control haul truck, drills.
	BHP Billiton	Coal	Underground	Control longwall shearer/system
	CMOC International	Copper, gold	Underground	Control loaders.
	Mandalay Resources	Gold-antimony	Underground	Control LH loaders.
	Rio Tinto	Diamond	Underground	Automation System.
	Rio Tinto	Iron Ore	Surface	Control haul trucks, drills, train, drones. Data management.
BRAZIL	Vale	Iron Ore	Surface	Control haul truck.
CANADA	ArcelorMittal Mines	Iron Ore	Surface	Data analytics.
	Barrick Gold/Teck Cominco	Gold	Underground	Control haul trucks.
	Hecla Mining	Gold	Underground	Automated loading/hoisting, tele-remote rock breaking, semi-autonomous drilling, mine/process monitoring.
CHILE	Codelco	Copper	Underground	Control mining, processing, transport.
SOUTH AFRICA	Anglo-American	Platinum	Underground	Intelligent connected mining, Control drilling and cutting.
	Anglo-American	Coal	Surface	Control dozer.
	Petra Diamonds	Diamond	Underground	Control haulage and transport systems.
SWEDEN	Boliden	Zinc, copper, lead, gold, silver	Underground	Control haul trucks, wheel loader. Ventilation automation, 5G network.
	Luossavaara-Kiirunavaara AB	Iron Ore	Underground	Autonomous drilling, loading, LADAR wall scanning.
UNITED STATES	Alliance Resources	Coal	Underground	Control longwall shearer.
	Arch Coal	Coal	Both	Control surface dozer.
	Barrick Gold	Gold	Both	Automation & data integration.
	Hecla Mining	Silver	Underground	Tele-remote loaders, automated trucks, VOD, mine/process monitoring, Big data.
	Newmont	Gold, copper, silver	Both	Control LHDs.

	Rio Tinto	Copper	Underground	Autonomous vehicles, data analytics, sensors network.
	Westmoreland Coal	Coal	Underground	Control longwall shearer.

For example, Rio Tinto has their "Mine of the Future ™ "initiative. The mining location is in the Western Australia Pilbara Operations at three surface iron ore mines, Yandicoogina, Hope Downs 4, and Nammuldi. All of the iron ore is moved using 71 fully automated, Komatsu driverless haulage trucks. They also operate 7 fully autonomous drill systems to drill production blast holes, and drones are being trialed to measure stockpiles and assist with environmental and maintenance activities. The Operations Center in Perth 1500 km away, acts as the systems "nerve center". There at the Operations Center, a team of 400 people monitor the entire Pilbara Operations in real time – right down to every truck. The full text of the article describing the adoption of automation at Rio Tinto can be found on their website (Rio Tinto, 2016).

Besides the mining automation activity in the Western Australia Pilbara Operations by Rio Tinto, BHP Billiton, and Fortescue, mining companies are adopting advanced technology on a much smaller scale, and many are just starting on a trial basis as a pilot project. Technology implemented or planned includes:

- Mobile machine monitoring & control – Monitoring includes sensors installed on machines for machine condition monitoring, and sensors that provide information for machine control. Machine condition monitoring includes temperature, pressure, flow, vibration, level, etc. Machine control includes sensors for machine position and navigation, sensors for keeping the cutting action in the ore seam, and sensors for machine function and operation. Also included are sensors for proximity detection and collision avoidance. Various levels of machine control are used including line-of-site remote control, tele-operation, operator-assist operation, and autonomous operation. Machines controlled include load-haul-dumps (LHDs), dozers, haul trucks, drills, loaders, longwall shearers, continuous mobile mining machines, and railroad trains.
- Mine monitoring – Most common is environmental monitoring such as CO, CH_4, and air velocity in underground mines. Monitoring could also include environmental parameters such as dust, diesel particulate matter, NO, NO_2, CO_2, H_2S, oxygen, temperature, barometric pressure, etc. This also includes ground movement, rock deformation, micro-seismic, and rock support monitoring. Drones are being used to measure stockpiles and to assist with environmental, reclamation, and maintenance activities on the surface.
- Fixed equipment and facility monitoring & control – Included are mine support systems such as fans, ventilation system components, power centers, conveyors, and dewatering systems, and ore processing plants such as crushers, mills, and preparation plants. Status monitoring, diagnostics and condition, and also control of function are included.

- Worker monitoring – Included are person-wearable monitors such as heart rate, temperature, physical location, activity (man down monitoring), proximity to moving equipment, and exposure assessment such as dust, noise.

Figure 1 shows the relationship of the key components of smart mine technologies, sensing (sensors), machine and equipment automation/control, and data analytics. Equipment used for extracting, hauling, and processing ore is monitored with sensors and controlled by line-of-site remote, tele-operation, operator assist, or autonomous operation. Fixed equipment used for support systems can be sensed and controlled. Workers can be monitored through wearable sensors. The environment can be monitored by fixed sensors, or by drones or mobile robots. All the sensed data (Big Data) is transmitted to a central location where it is sorted, analyzed, modeled (Data Analytics) and used for decision making and for machine control.

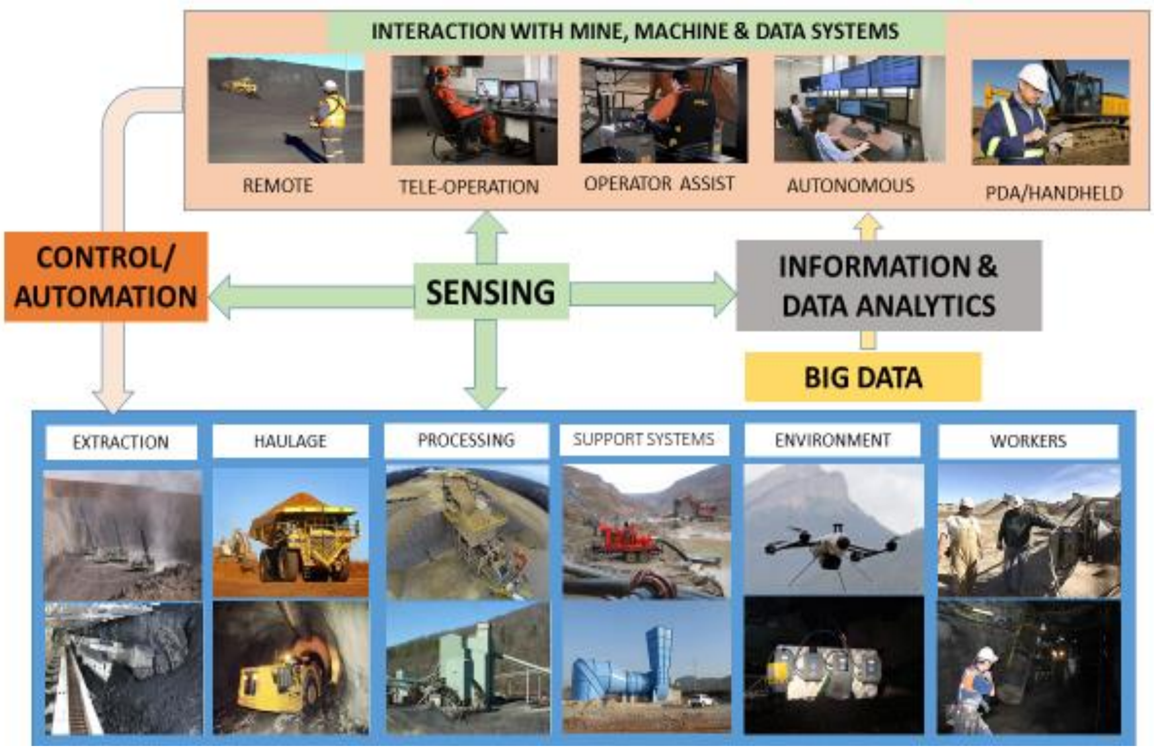

Figure 1- Relationship of key components of smart mine technologies.

In the U.S., in underground coal mines, a number of parameters have been monitored including carbon monoxide, methane, air velocity, and the status of conveyor belts and fans. More recently, mines are required to provide electronic tracking of workers underground, and proximity warning systems on the continuous mining machines and other mobile equipment including scoops and shuttle cars. Mines have also monitored ground movement and roof support status, and the operating status of extraction and haulage equipment for preventive maintenance and diagnostics. Surface mines have also monitored conveyor status, and the operational status of other fixed equipment, along with machine condition monitoring. Ore processing plants and mills have various process monitoring, and are automated to some extent.

Some underground coal mining companies have implemented mimic cutting on their longwall shears, where the shearer is manually controlled for one direction of cutting and then the cutting for the opposite direction is automatic. Other mining companies are controlling their longwall shearers remotely underground. Most longwall systems have automatically advancing shields. In surface coal mining, one mine uses a semi-autonomous dozer for mining operations and another uses a remote-controlled dozer on coal stockpiles to protect the operator from injury where dozers have been buried by coal stockpile collapse.

In the U.S., several metal mining companies are implementing smart mine technologies. Newmont uses a semi-autonomous LHD in their operation in Nevada. Barrick Gold has a pilot study now for automation and data integration, and is using Hexagon's SAFEmine collision avoidance and vehicle tracking information system in their Nevada operations. Hecla Mining Company is implementing tele-remote loaders, automated trucks, collision avoidance on all equipment, ventilation on demand, monitoring and control using wireless data collection, equipment and worker electronic tracking, equipment operational data and health monitoring, geotechnical monitoring, environmental monitoring, and "Big Data", with tablet computer interaction for their Alaska mining operation. For their Idaho mine, Hecla is planning an Atlas Copco hard rock mobile vein mining machine that can be operated tele-remotely. It will use automated loaders or trucks behind the machine to transport the ore. The mine is monitoring the environment, and seismic and deformation response of rock mass wirelessly. Lastly, for their Quebec operation, Hecla has implemented automated loading and hoisting of ore and waste, tele-remote rock breaking from the surface, semi-automation of face drilling and longhole blasthole drilling, autonomous truck haulage, and mine environment, equipment, and process monitoring (Lopez-Pacheco, 2017). At U.S. stone mines, based on available information, we believe that crusher plants are the only place automation is being used. At surface mines drones are being used for stockpile measurement, mine planning, and inventory management.

In other countries, there is also a significant amount of interest in smart mine technologies, including autonomous mining. Canada has some autonomous haul trucks, remote control LHDs, and Big Data analytics using OSIsoft. Brazil, Chile, South Africa, Sweden, and Eastern Australia also have semi-autonomous or autonomous operation of haul trucks, dozers, loaders and/or drills on various scales of implementation. The European consortium on Sustainable Intelligent Mining Systems (SIMS) is a mining industry initiative funded by Horizon 2020, a European Union research and innovation program. The consortium is made up of 11 organizations from Sweden, Finland, Germany and Poland. Atlas Copco is the coordinator, and ABB, Agnico Eagle, Boliden, Ericsson, KGHM Cuprum, K+S KALI, LKAB, Mobilaris, Lulea University of Technology and RWTH Aachen University are members. Each

SIMS consortium partner is to demonstrate their new advancements in working mines around Europe. http://SIMSmining.eu

Figure 2 shows the location of mines that have implemented, or plan to implement smart mine technologies in their mines. Mine location is shown by a diamond, with the color of diamond indicating type of mine, surface or underground mine, or both.

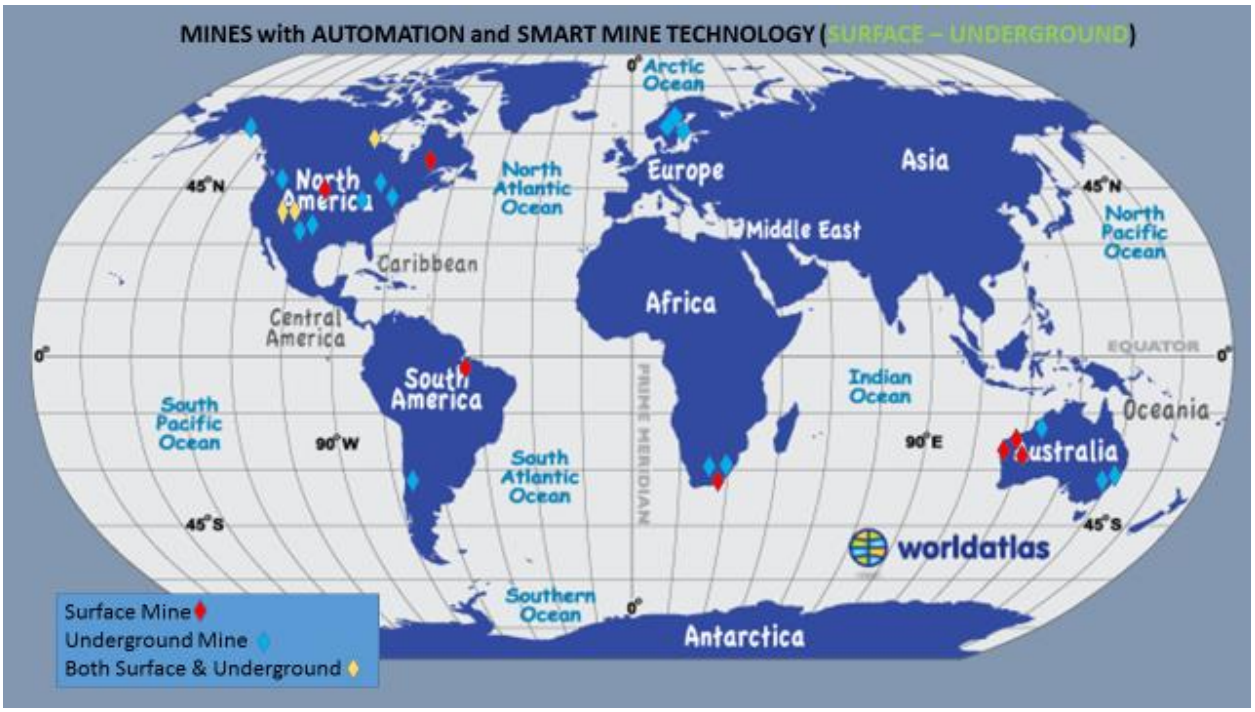

Figure 2. Mines that have implemented, or plan to implement smart mine technologies.

For this figure, smart mine technologies refer to disruptive technologies associated with remote control and automation of equipment, wireless communications, smart sensing, interconnectivity of devices, or data analytics. The data presented on the map represents our current state of knowledge based on publically available information and may under report the true status of smart mine technologies adoption in the U.S.

Appendix A provides a detailed listing of mining companies from around the world that are already employing smart mine technologies. All mines indicated in the world map above are listed in the appendix. Although no mines are fully autonomous, it is likely this will happen in the near term future as the mining industry looks to find ways to increase productivity (Jensen, 2016).

Figure 3 depicts companies and universities that have major roles in supplying, implementing, or guiding the adoption of autonomous systems, big data analytics, and smart mine technologies in mining. Appendix B provides a detailed listing of each company or university in the landscape diagram along with the web link. It should be noted that this list is not exhaustive.

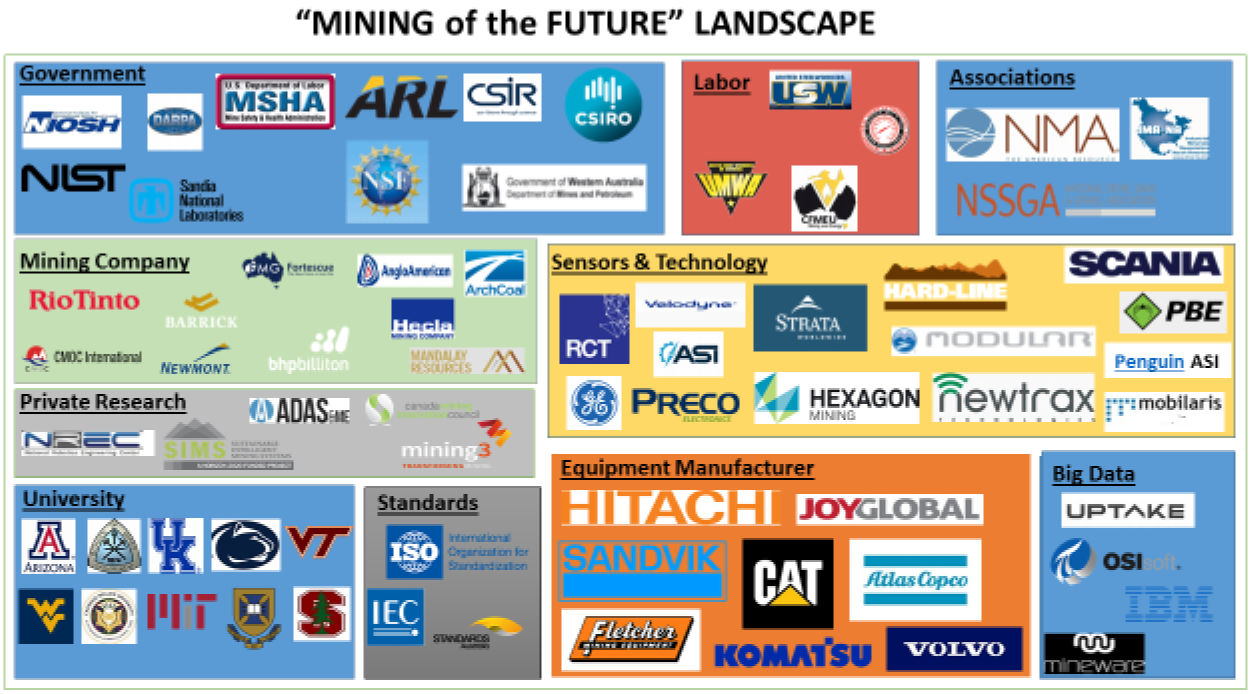

Figure 3. A landscape diagram depicting companies and universities that have major roles in supplying, implementing, or guiding the adoption of smart mine technologies including autonomous systems and big data analytics.

Appendix C lists standards that have some applicability to mining. "ISO 17757 – Earth-moving machinery and mining — Autonomous and semi-autonomous machine system safety" is the only standard specific to mining. In addition, Code of Practice – Safe mobile autonomous mining in Western Australia, was developed by the Department of Mines and Petroleum, Resources Safety in 2015 (DPM, 2015) to provide guidance on mobile autonomous and semiautonomous systems used in surface and underground mines and quarries, and develop and evaluate safe work procedures for such systems.

3.0 Research Focus Areas

External companies and academia have expertise in developing smart mine technologies and conducting mining automation research. Some of the leading research organizations for mining automation include Carnegie Mellon University National Robotics Engineering Center, and Commonwealth Scientific and Industrial Research Organization, Australian Government (CSIRO). The leading equipment providers in the global smart mining market include Hitachi Construction Machinery Co. Ltd., ABB Ltd., Komatsu Ltd. (including their Joy Global Inc. group), Outotec Oyj, Atlas Copco, Sandvik, and Caterpillar Inc. (Staff, 2016). While NIOSH expertise specific to mining automation is limited, researchers possess extensive knowledge in topic areas directly related to the development and integration of technologies applied to enable automation. Rather than developing smart mine technologies, NIOSH should take a proactive approach in focusing on research areas concerning health and safety implications with smart mine technologies given our strength in health and safety research.

Six research focus areas that could serve to guide our research direction and the expenditure of resources to achieve our vision of "proactively address worker health & safety associated with disruptive mine technologies", have been identified. Collectively, the six research focus areas comprise a conceptual framework that describes the most relevant research areas and the relationships that exist between them, and challenges that must be addressed to understand mine worker health and safety as it relates to disruptive technologies in the mining industry.

Several methods were used to identify the six focus areas. First, mine of the future committee members systematically identified potential focus areas based on their expert knowledge and experience. In a parallel effort, a literature review was conducted to identify current and future trends in disruptive technologies in the mining industry. The literature included trade publications, market forecasts, and industry reports (BMI Research, 2015; PR Newswire, 2017; Cosbey et al., 2016; Sheridan, T., 2016; Jensen, 2016; Staff, 2016). External experts in mining automation and robotics at Carnegie Mellon University National Robotics Engineering Center were also contacted to identify critical research areas. Pertinent information was obtained from the NIOSH Center for Occupational Robotics Research which has numerous contacts with industry experts in the area of industrial robotics and automation. Finally, for each research focus area, an analysis of the health and safety implications related to that focus area was performed. This analysis helped identify the most critical areas for research and those with the greatest potential for immediate impact.

Figure 4 depicts the focus areas established from the initial industry review. Note that the size of each focus area does not infer importance but serves only to enable illustration of how each focus area is interrelated. For instance, the focus area of sensors is directly related to automation, data analytics, and situational awareness. Automation is highly dependent upon sensors to provide input; sensor data for automation can be used for data analytics, and can provide critical sensor-based information for improving situational awareness.

Figure 4. A Venn diagram depicting the primary interrelationships among research focus areas. Note that focus area size does not infer importance but serves only to enable illustration.

Figure 5 serves to further illustrate the interrelationships among several focus areas. System safety analysis would identify sensor-based data that a miner would need to receive from the mine environment in order to reduce the risk of an accident. Moving left to right within Figure 5, the data are provided from the mine environment; human factors plays a role to determine the most needed data and the most effective interface to provide the mine worker data for situational awareness so that the mine worker can make an informed decision for the most appropriate response; human factors again plays a role to determine the most effective interface to provide a response. Figure 6 depicts the distinction between human factors and situational awareness where the essence of human factors concerns the interactions between the "world" and the human while situational awareness focusses on the human's cognition. The level of cognition is very low for a simple, non-automated process but it becomes critically important to focus on cognition for automation because even a short lapse in situational awareness can have catastrophic results in complex, automated systems (Endsley, 1995). Many elements of human factors may impact and play a role in situational awareness and the processes used to analyze it, such as attention, memory, training, and stress. However, these elements are distinct from situational awareness and vary independently from it (Endsley, 1995). This distinction is important given that situational awareness becomes more critical and more difficult to attain as automation complexity increases. The modeling, measurement, and assessment of situational awareness is largely based on cognition and requires a focus and skill set that differs from human factors.

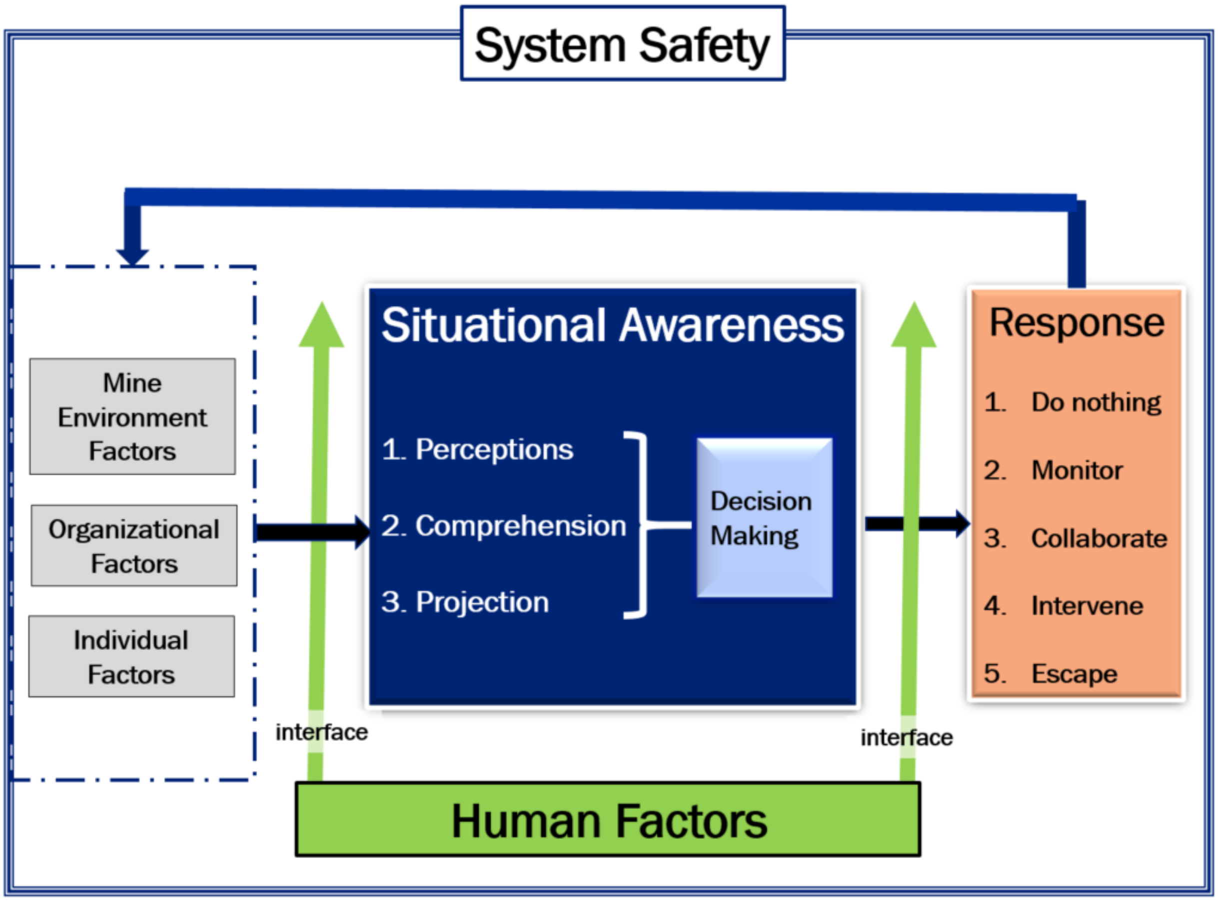

Figure 5: A model depicting how the research focus areas of human factors, situational awareness, and system safety are interrelated.

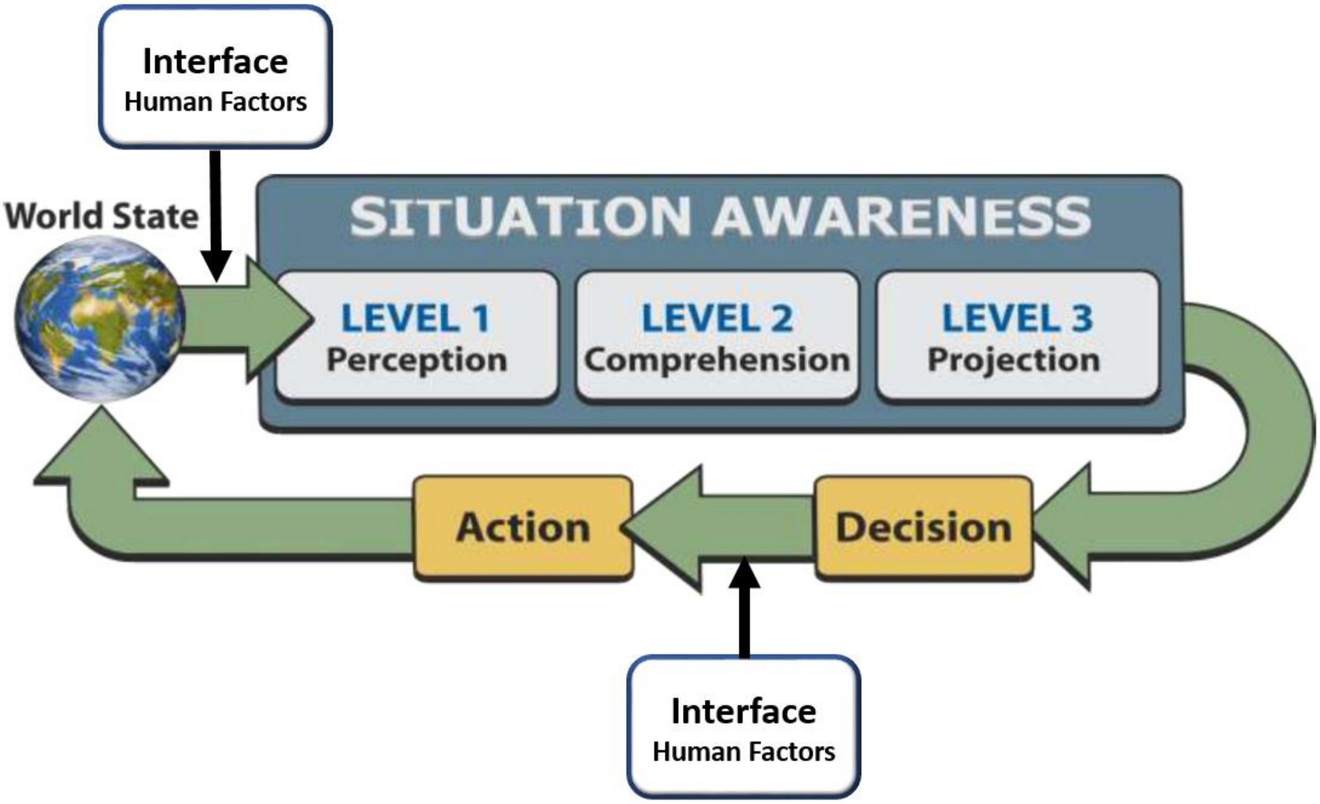

Figure 6 Human factors and situational awareness. Adapted from the Endsley model of situational awareness (Onal et. al, 2012)

3.1 NIOSH Workforce

The NIOSH workforce has expertise in several research focus areas related to integration of smart mine technologies. Future research in this area will require identifying the expertise possessed and the demonstrated proficiencies, as well as the knowledge gaps and development needs for the organization. Some of these competencies exist within the organization and some competencies will need to be obtained via new hires, external contracts, or development plans for current employees. The NIOSH mining leadership is in the process of developing a Workforce Development Plan for PMRD and SMRD that will assist in developing researchers and staff to meet the human resource needs of mining projects. The plan consists of identifying critical competencies, assessing proficiency levels, and creating development plans to meet the critical needs of achieving specific tasks on active and future projects identified in the program's strategic plan. Competencies have been identified by the NIOSH Mining lead team and are based on the project needs. Proficiency ratings are based on the NIH 5-level Proficiency Scale, which is designed to measure one's ability to demonstrate a competency on the job. Level 1 is Fundamental Awareness, 2 is Novice, 3 is Intermediate, 4 is Advanced, and 5 is Expert. Assessing the needs for the Mine of The Future effort is dependent on the workforce assessment exercise to determine competencies and proficiency levels for the PMRD and SMRD. Accordingly, this summary includes relevant competencies and level of proficiency needed to achieve successful completion of the specific tasks.

The levels of competency (NIH 5-level Proficiency Scale) are categorized as follows for each research focus area:

Score	Proficiency Level	Description
N/A	***Not Applicable***	You are not required to apply or demonstrate this competency. This competency is not applicable to your position.
1	***Fundamental Awareness*** (basic knowledge)	You have a common knowledge or an understanding of basic techniques and concepts. • Focus is on learning.
2	***Novice*** (limited experience)	You have the level of experience gained in a classroom and/or experimental scenarios or as a trainee on-the-job. You are expected to need help when performing this skill. • Focus is on developing through on-the-job experience; • You understand and can discuss terminology, concepts, principles, and issues related to this competency; • You utilize the full range of reference and resource materials in this competency.
3	***Intermediate*** (practical application)	You are able to successfully complete tasks in this competency as requested. Help from an expert may be required from time to time, but you can usually perform the skill independently. • Focus is on applying and enhancing knowledge or skill; • You have applied this competency to situations occasionally while needing minimal guidance to perform successfully; • You understand and can discuss the application and implications of changes to processes, policies, and procedures in this area.

4	***Advanced*** (applied theory)	You can perform the actions associated with this skill without assistance. You are certainly recognized within your immediate organization as "a person to ask" when difficult questions arise regarding this skill. • Focus is on broad organizational/professional issues; • You have consistently provided practical/relevant ideas and perspectives on process or practice improvements which may easily be implemented; • You are capable of coaching others in the application of this competency by translating complex nuances relating to this competency into easy to understand terms; • You participate in senior level discussions regarding this competency; • You assist in the development of reference and resource materials in this competency.
5	***Expert*** (recognized authority)	You are known as an expert in this area. You can provide guidance, troubleshoot and answer questions related to this area of expertise and the field where the skill is used. • Focus is strategic; • You have demonstrated consistent excellence in applying this competency across multiple projects and/or organizations; • You are considered the “go to” person in this area within PMRD and/or outside organizations; • You create new applications for and/or lead the development of reference and resource materials for this competency; • You are able to diagram or explain the relevant process elements and issues in relation to organizational issues and trends in sufficient detail during discussions and presentations, to foster a greater understanding among internal and external colleagues and constituents.

3.2 Situational Awareness

Definition

Situational Awareness (SA): The perception of elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future (Figure 7) (Endsley, 1995).

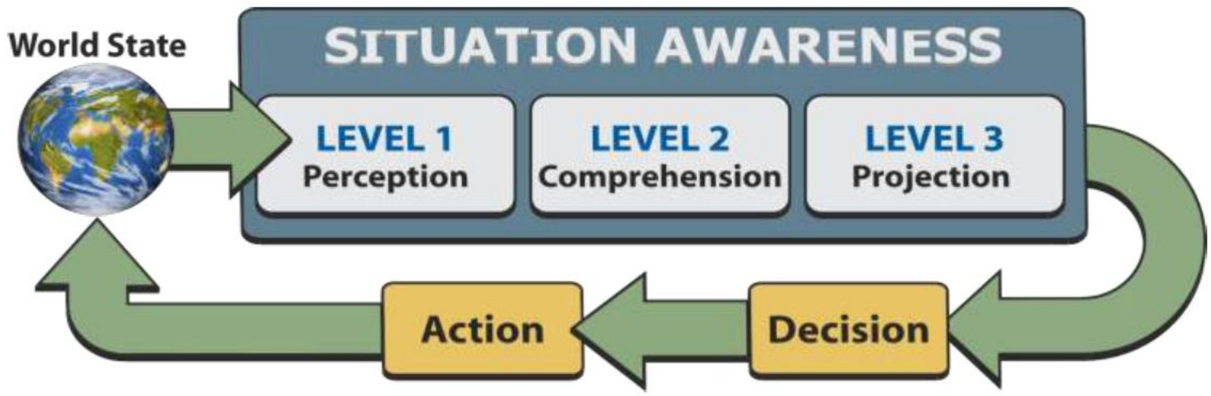

Figure 7. The Endsley model of situational awareness (Onal et.al, 2012).

Background

A recent National Academy of Sciences (NAS) National Research Council (NRC) Division of Behavioral and Social Sciences and Education report (hereafter referred to as "the NAS report") recommended the development of human-centered technologies to improve SA and enhance self-escape from underground coal mines (NRC 2013).

SA is especially challenging for mining given inherent physical barriers: a dynamic mine environment, moving machinery, noise, dust, piecemeal addition of technologies, limited fields-of-view, etc. Other human-centered SA barriers include fatigue, shift work, and poor lighting (Endsley and Jones 2013).

SA forms the foundation of all decision-making, problem resolution, task execution, performance, and safety (SA Technologies, 2012). Inadequate SA can result in poor decisions or errors that could negatively impact safety. The importance of SA for mining has multiple applications:

- Workers operating or monitoring autonomous and semi-autonomous equipment
- Workers using non-line of sight, tele-remote technologies to operate equipment (i.e. underground mining equipment operated from a surface location that is miles away from the mine)
- Workers in the vicinity of autonomous and semi-autonomous equipment

- Workers doing maintenance and repair of autonomous and semi-autonomous equipment that likely elevates the risk of injury because these activities place people in more direct contact with the equipment.
- Emergency response teams' situation awareness and decision-making are critical given that the lives of trapped mine workers depend on the teams' decisions (Fuller, 2014).
- Effective SA is needed to enhance self-escape from underground coal mines (NRC 2013).
- Operators of atmospheric monitoring systems (AMS) must be able to process information displayed and must be trained on what alarms mean. This is especially important with the growing complexity of mine communications centers technology relative to emergency situations.

Health and Safety Implications

The challenges for achieving and maintaining SA will only increase as mining automation becomes more prevalent and more complex. In general, as automation increases, SA decreases. "*The attempt to automate our way out of so-called human error has only led to more complexity, more cognitive load and catastrophic errors associated with losses of situational awareness.*" (Endsley, 1995). This is true for mining because automated and semi-automated mining equipment and mining processes are very data-driven and typically result in less worker interaction. As a result, there are greater barriers to mining automation SA because:

1) systems become much less transparent to the worker because the worker has a reduced comprehension of the state of automation and the various operational parameters and data;

2) workers can have data overload because systems can present more data than a worker can understand (for example AMS operators);

3) the worker experiences the out of the loop syndrome due to factors such as complacency, inadequate system feedback, reduced awareness of the automation state, and boredom (Endsley and Jones 2013)***.***

4) the SA challenges will increase as the level of automation increases, and systems become more reliable and robust in efforts to improve productivity. As automation, reliability, and robustness increases, situational awareness decreases thus decreasing effective human monitoring and intervention (Endsley and Jones 2013)***.***

A study of human errors resulting in mine fatalities identified these contributory factors: a failure to perceive or recognize a warning, failure to respond to a perceived or recognized warning, ineffective response to a warning, and underestimation of the hazard (Dhillon, 2015). These situational awareness issues are exacerbated for automated, semi-automated, and tele-remote mining equipment given the many barriers to situational awareness which is a fundamental prerequisite for effective human factors research. Accidents involving mobile autonomous and semi-autonomous mining vehicles have occurred (DPM, 2014). The contributory situational awareness issues include an inappropriate response to system information or warnings, misinterpretation of system information or ignoring warnings, lack of knowledge and understanding of the autonomous equipment operation, and not adhering to personnel or equipment exclusion zones (DPM, 2014).

SA is as important for all underground or surface mine workers as it is for miners working in remote areas or alone. Mine workers must be aware of all mine environment factors including: their location, ground control conditions (including pit and roadway), mine atmosphere, equipment operating, and more. Miners working in production sections with their crews must also be aware of similar factors along with their crewmate's activities. As more mine processes and the mine environment are monitored, there is an opportunity to use virtual reality and visualization systems to view that data, including mine geometries and mapping information, microseismic data, stresses and deformation data, to improve situational awareness.

Current Research

There appears to be very limited mine worker health and safety research related to mining SA research external to NIOSH. The SA research is narrowly targeted to surface mining shovels. SA Technologies, Inc. was tasked by the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Mining Standards and Guidelines Committee (MSGC) to apply the situational awareness-oriented design process to electric shovel mining equipment user interface design. The objective was to develop a single, unified common user interface for large shovels to maximize the shovel operator's experience, safety, and ability to make decisions (SA Technologies, 2012). The CIM Global Mining Standards & Guidelines Group (GMSG) has a SA workgroup. The GMSG *"facilitates global mining collaboration on solutions to common industry problems, needs and technology through standards, guidelines and best practices. GMSG operates on the five principles of inclusivity, collaboration, innovation, optimization and technology"* (GMSG, 2017). The GMSG SA Workgroup objective is to *"Develop operator-driven design guidelines for the development of a unified common user interface for large shovels; aid the creation of common interfaces – in-cab screens that incorporate multiple onboard systems into a single presentation – to maximize the shovel operator's experience, safety, and ability to make decisions."*. The full text of the situational awareness efforts can be found on Global Mining Standards page at http://www.globalminingstandards.org/working_group_categories/situation-awareness-sa/.

There are a few current NIOSH mining projects that have some SA research components as follows: "Enhancing Mine Workers Abilities to Identify Hazards at SSG Mines" project seeks to understand how cognitive processes, such as attention and risk perception, are involved in hazard recognition; "Design of Proximity Systems for Underground Mobile Equipment" has a research task concerning the effectiveness of warnings that involves the three stages of SA; "Improving Situational Awareness Through Visual Interventions" addresses the visual perception and comprehension stages of SA. However, NIOSH SA research is not being conducted in the context of robotics and automation which places more and different challenges on establishing and maintaining SA.

NIOSH Comparative Advantages

NIOSH is well suited to conduct SA research given the expertise in conducting worker safety research versus production. NIOSH has some SA expertise in the context of mining safety. SA research will require human subject qualatative and quantative testing expertise which NIOSH has in the setting of a laboratory and in the field. NIOSH has also conducted research in mining machine safety that is applicable to automation (e.g. intelligent proximity detection, intelligent lock out/tag out, system safety of programmable electronic mining systems). NIOSH also has expertise in human factors, organizational psychology, and worker behavior all of which play important roles in SA.

Outcomes and Risks

An expected outcome of this research will be an overall improvement on the health and safety of mineworkers because effective SA will enable mineworkers to: better recognize operational hazards and system failures, and then intervene to take appropriate corrective actions; reduce human error due to information overload and a lack of system transparency (Endsley and Jones 2013). Lastly, SA is not unique to mining, thus there are opportunities to translate NIOSH SA research to other industries.

Smart mine technologies will continue to play an ever-increasing and dominant role in surface and underground mining regardless of research that NIOSH conducts. Failing to establish a groundwork for the development and acquisition of skills and resources specific to SA may greatly diminish the relevancy of NIOSH. Secondly, if a mining disaster occurs involving smart mine technologies, then NIOSH has the potential to be negatively placed in the forefront of the general public, congress, and the labor unions because NIOSH did not adequately meet the expectations of enhancing health and safety through the investigation of SA for smart mine technologies.

Competencies

Competency	Level	In-house competency	Specific needs
Situational Awareness/Risk Perception	5	Yes	Additional expertise is needed at a 4-5 competency level. SA experience with robotics or automation is highly desired. A potential contractor is SA Technologies http://satechnologies.com/ who can conduct research and provide training
Behavioral change theories	5	Yes	None
Surface/Underground mining methods	5	Yes	None
Mine equipment operation and design	3-5	Yes	None

Facilities Needed

A facilities overview is provided in Appendix D.

- VisiLab (existing). No major VisiLab modifications are needed.
- Safety research coal mine and the experimental mine (existing). Major upgrades are needed and are already in progress.
- Surface and underground mines. Cooperating mine sites are needed which have been increasingly difficult to obtain.
- Human performance research laboratory (existing): No major laboratory modifications are needed.

3.3 Automation

Definitions

Automation: Automation traditionally refers to a process or piece of equipment that operates automatically, usually under some level of computer control.

Robotics: Robotics is related to automation and typically refers to a machine that automatically performs a task or process in place of a human.

Robotics and automation can be semi-autonomous (some human intervention needed) or fully autonomous. However, the term robotics is not typically used for mining machines in the industry. For example, haul trucks with no human operator are referred to as autonomous trucks. An LHD that trams by itself, but requires a remote human operator to assist with loading, is referred to as semi-autonomous (also called tele-remote) or operating under supervised autonomy.

Figure 8 Terregator robot developed by CMU in partnership with NIOSH for mine mapping.

Background

Economics, safety, and human resource limitations are all influencing a push toward autonomous mining equipment. While the majority of automated equipment involves surface mining haulage fleets, underground mines are experiencing the same pressures and seeking the same answers through technology (Paraszczaka et al, 2015, Norton, 2017). In addition, advances in control and communications technology have allowed other processes to be automated including mining at the face, ventilation, atmospheric monitoring, and drilling to name a few.

Automation and robotics are also being applied to mine rescue operations to improve the quantity, quality, and timeliness of information made available to emergency responders. NIOSH mine rescue robotics efforts include the following:

- A prototype Snake Mine Rescue Robot capable of being deployed thru a 5" diameter mine borehole to depths up to 2000 ft. Once in the mine, the robot can gather and transmit pertinent information for responders.
- The Gemini Scout Robot for scouting in advance of mine emergency response.
- The remotely-controlled Mine Rescue Team Support Vehicle (Mule) for carrying rescue supplies, monitoring environmental conditions, and aiding search efforts.
- Aerial robots (unmanned aerial vehicles) for use in mine rescue and monitoring efforts.

Health and Safety Implications

Concerns with safe-design of automated mines and machines are already being raised along with reports of near-misses (DPM, 2014). Standards and industry organizations are now starting to develop guidelines for implementation of automated and semi-automated equipment (EMESRT, 2016; ISO 17757, ISO 21815). Australia is considered the leader on automation safety standards due to their push to develop global standards for automated mining operations. The full text of their efforts can be found at the mining technology webpage at http://www.mining-technology.com/features/featureaustralias-input-on-automation-safety-standards-4497556/. NIOSH involvement in these efforts should be initiated immediately to ensure these efforts are informed by current safety research and to aid in dissemination to US mines.

Top safety concerns mainly involve the inevitable interaction of human workers with automated equipment:

- Humans or human-operated machines and automated machines sharing the same roads or work areas
- Human interaction with automated machines during maintenance

- Human-Machine Interface design and task overload
- Sensor and control system reliability
- Fail-safe design
- New standards and regulations
- Training and deployment for effective use of mine rescue robots

Current Research

Major efforts in research related to mining automation are occurring at many schools and industry-sponsored research organizations such as Carnegie Mellon University, CSIRO, and others. Enabling technologies for automated machines for coal mining were developed by the US Bureau of Mines in the 1980s and 90s, and some of that expertise remains in NIOSH today. Most of the major OEMs (e.g. Caterpillar, Komatsu, Hitachi, Sandvik, Volvo) have implemented or are now testing automated mining equipment including haul trucks, dozers, drills, and shovels. In addition, several technology companies have entered the retrofit market for outfitting a mine's existing fleet with after-market automation solutions, such as Hexagon Mining and ASI.

Australia-based mining operations, such as those run by Rio Tinto and BHP, are moving in this direction faster than other countries (Rio Tinto, 2013; Bellamy and Pravica, 2011). However, trials of the technology are also occurring in South America, Canada, and the US. The full text describing some of these efforts, including Komatsu's installations in Canada and Caterpillar's installation in the USA can be found on the Mining web page at http://www.mining.com/canadian-oil-sands-giant-testing-autonomous-haul-trucks/. Safety research dedicated to the implementation of automated mining equipment is not a fully developed field and is not receiving the needed attention when considering the risk factors. NIOSH and Australian universities (Lynas and Horberry, 2011) have had limited efforts in this area, and industry organizations like the Earth Moving Equipment Safety Round Table (EMESRT) also are reacting to emerging safety research needs being raised by mining companies.

Research proposals to: 1) update the functionality and apply for MSHA permissibility of the Mine Rescue Mule, and 2) design and develop a drone capable of automated mine monitoring and communication have been submitted and are undergoing evaluation. MSHA have trained with and evaluated the functionality of both the Snake and Gemini Scout robots for use during mine rescue efforts, although both units were prototypes, not designed for routine use, and are currently awaiting repair with limited functionality.

NIOSH Comparative Advantages

The top concerns in the area of automation are focused on safety and human factors. NIOSH is uniquely qualified to proactively address emerging safety concerns related to automation as part of its current mission and has the expertise, resources, and a proven track record in proposing forward-looking safety research. The Mining Program has expertise in critical areas, including human factors, engineering, and system safety design. These competencies and the program capacity in these areas should be further developed to plan for long-term research in the area of automation. In addition to expertise, NIOSH is uniquely positioned to contribute to establishing standards and guidance through active involvement in standards committees and global work groups. NIOSH is involved in groups such as EMESRT, ANSI, and ISO committees and this will enable researchers to build collaborative partnerships to impact the industry directly. Cross-sector collaborations should also be leveraged to enable NIOSH to leverage initiatives such as the robotics safety research to further position NIOSH as a leader in automation safety research. Overall, NIOSH is well positioned to make a significant contribution to the advancement of automation technologies and integration practices.

Outcomes and Risks

An expected outcome of this research will be guidance and best practices for designing safe work environments, along with safe design principles for control systems and machine interfaces needed as US operations and equipment manufacturers move toward more automated machinery/processes. NIOSH should take a proactive approach in determining emerging health and safety implications. If these issues are not addressed in the early stages of automation planning and deployment in the US, NIOSH may find itself in a reactive role after injuries and fatalities start occurring.

Competencies

Competency	Level	In-house competency	Specific needs
Robotics (Electrical and Mechanical Design)	4	Yes	Additional expertise is needed at 4 competency level. Contractors are an option for specific specialties.
Systems Engineering	5	Yes	Additional expertise is needed at 5 competency level.
System Safety Principles	5	Yes	Additional expertise is needed at 5 competency level related to automation systems design.
Human Centered Design	5	Yes	Additional expertise is needed at 3-5 competency level.
Cognitive Psychology	3-5	Yes	Additional expertise is needed at 3-5 competency level.
Ergonomics	3-5	Yes	Additional expertise is needed at 3-5 competency level.
Behavior change theories	3-5	Yes	Additional expertise is needed at 3-5 competency level.

Facilities Needed

A facilities overview is provided in Appendix D.

- Safety research coal mine and the experimental mine (existing). Major upgrades are needed and are already in progress.
- Surface and underground mines. Cooperating mine sites are needed that are implementing automation technologies.
- Human performance research laboratory (existing): No major laboratory modifications are needed.

3.4 Data Analytics

Definition

Data Analytics: The process of extracting information from raw data using specialized statistical computer systems. These systems transform, sort and model the data in order to discover patterns and meaning. Today, most research in data analytics appears to be focused on Big Data. Big Data Analytics is characterized by three factors: volume, in that there is too much data to handle easily; velocity, in that the speed of the data flowing in makes it difficult to analyze; and variety, in that the types of data are too broad to easily process. Compared to traditional data analytics, big data analytics promises to provide richer insight since its data is drawn from multiple varied sources. Moreover, these factors require new computational and data-handling methods. There are four main categories of Big Data Analytics:

1. Descriptive analytics, or data mining, used to discover what is happening now based on the incoming data;
2. Diagnostic analytics, used to discover what happened in the past and why;
3. Predictive analytics, used to discover what might happen in the future based on current information; and
4. Prescriptive analytics, used to reveal what actions should be taken based on the incoming data.

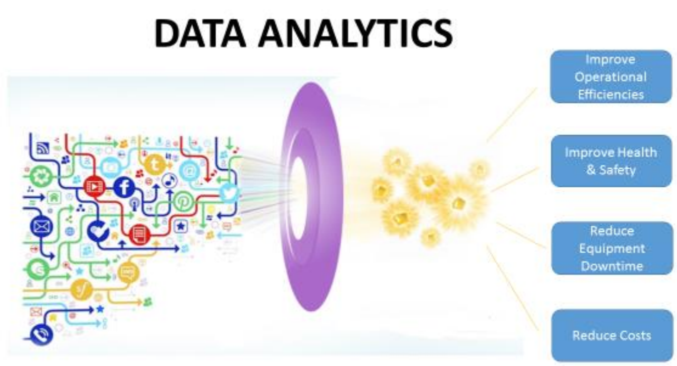

Figure 9 Data Analytics Outcomes

Background

Traditional data analytics is integral to effectively managing operations in terms of improving operational efficiencies, improving health and safety, reducing equipment downtime, and reducing costs (Figure 9). It is critical to health and safety as a tool to discover trends in accident statistics and other health problems observed in the workforce. It is also applied to real-time sensor information in process networks that can inform an operator of unsafe or unhealthy conditions currently occurring in their operation. Traditionally, separate systems for plant operations, miner tracking, and ventilation have led to data siloing, preventing sharing between systems. By removing these silos big data analytics promises to improve health and safety outcomes by discovering patterns not readily apparent from the individual datasets. Historical data can provide an indication of what might happen in the future. By understanding signals from sensors, machines and other data sources, predictive analytics can predict future events so that a mine operator can become more proactive. This new way of thinking has led to new forms of data collection, storage, and processing as evidenced by the explosion of interest in the industrial Internet of Things.

The World Economic Forum describes the Industrial Internet of Things as a "combination of the global reach of the Internet with a new ability to affect or provide outcomes in the physical world, including the machines, factories, and infrastructure that define the modern landscape." The Internet of Things (IoT) is about devices, connectivity, and data. It is the means that collects and sends massive amounts of data from internet-connected devices. Big data analytics are the tools that handle the masses of data and draw on it to create insights for decision making. Interconnected devices will likely not only provide positive economic outcomes but improvements to miner health and safety as well. In terms of health and safety, the Industrial Internet of Things involves using pervasive sensing to discover and sense the current dangers or unhealthy conditions in the workplace and provide automatic corrective or proactive action or otherwise provide a positive health and safety outcome. Real time data from sensors and the industrial control system will be augmented with data from other business analytics to provide timely predictions and prescriptions.

Health and Safety Implications

Some companies are beginning to look beyond traditional safety strategies like root-cause incident analysis, safety culture improvement, and training to big data analytics for further reductions in injuries and fatalities. If injuries can be predicted accurately, work environments can be modified and workers can be trained, to prevent injuries. The data potentially relevant to predicting injury or disaster are plentiful: prior safety experience; a worker's age and time in a specific job; time during a shift and hours worked during the prior day, week, or month; geographic location; how recently a workplace inspection occurred, and what the results were; season; enterprise profitability; the presence of an injury prevention program; and union representation of the workforce for example (Wagner, 2014).

Another approach to reducing injuries using data analytics is through equipment condition monitoring. Monitoring equipment vibration through remote sensors, for example, can be used to predict failures and needed maintenance, thereby reducing worker exposure to hazards during maintenance activities.

Current Research

New research and applications of big data analytics are occurring in many industries. Smart cities, smart cars and improved delivery of healthcare are some examples. Health and Safety studies have been performed in transportation, oil and gas, and public safety systems but Big Data is in its infancy and much of its promises are yet to be realized. Two online publishers that are beginning to discuss applications of Big Data in Safety and Health are the American Society of Safety Engineers (a professional society publishing standards as well as technical publications) and Occupational Health & Safety. At least three software vendors offer big data products/consulting targeted to Health and Safety, Spacetime Insight, Predictive Solutions, and SAS.

NIOSH Comparative Advantage

Overall, NIOSH does not have a comparative advantage because it does not possess expertise in analyzing big data, but does have staff well versed in traditional analytics and surveillance. There are a number of competencies relevant to the execution of big data analytics which NIOSH does not currently possess and thus should become a focus for hiring and development plans moving forward. Competencies such as predictive modeling, statistical algorithms, and what-if analysis are needed.

Outcomes and Risks

An expected outcome of research in this area would be guidance on effective application of data analytics applied to health and safety concerns in the mining industry. The industrial application of Big Data processing to worker health and safety is in an early stage. The NIOSH mining program has the potential to identify how Big Data analytics can be used to improve mine worker health and safety. NIOSH should continue to monitor the advancements and applications of safety and health in Big Data and the Industrial Internet of Things to guide future involvement. If research gaps become apparent, training of existing staff, hiring, and leveraging mine operator partnerships to access relevant data sets may be necessary. An underlying risk in investigating application of data analytics to enhancing health and safety in mining relates to accessibility to real data and mine operations leveraging smart mine technologies. As such, collaborative efforts/partnerships with mining companies will be critical to the advancement of research in this area.

Competencies

Competency	Level	In-house competency	Specific needs
Advanced Data Analytics – predictive modeling, statistical algorithms, what-if analysis	5	No	Expertise is needed at 5 competency level.
Instrumentation/Sensors/Networking	5	Yes	None
Public Health Surveillance	3-5	Yes	None
Data engineering	5	Yes	None
NoSQL/SQL database management	5	Yes	None
Machine learning	5	No	Expertise is needed at 5 competency level.

Facilities Needed

- None

3.5 Human Factors

Definition

Human factors: The systematic application of relevant human characteristics, abilities, expectations, and behaviors to the design and operation of tools, machines, procedures, and facilities (Sanders and Peay, 1988). The major objective for human factors in the workplace is to enhance the effectiveness, efficiency, and safety of human interactions with what they use to perform their jobs.

Background

The mining industry has identified human factors as a critical health and safety component of technology especially as mining machines become more advanced (Peterson et al, 2001). With respect to mining machines, human factors focusses on the worker-machine interactions as they operate, monitor, maintain and repair mining machines. Thus, the interfaces among the humans, hardware, and mine environment are critical. These interfaces become especially challenging for automated, semi-automated, and tele-remote mining equipment that are very data-driven from sensor inputs and much more complex than traditional mining systems. The human role, in terms of a decreasing frequency of interaction, now becomes that as a collaborator, a monitor having oversight, and as an intervener when the system goes awry or an emergency situation arises. Situational awareness "drives" the human interaction with the machine; human factors enhances these human interactions. As automation increases, situational awareness becomes critically important thus it is a separate research area described later in this document.

Health and Safety Implications

Automation "changes the nature of the work that humans do, often in ways unintended and unanticipated by the designers of automation" (Lynas and Horberry, 2011). These unintended and unanticipated ways can create new risks or exacerbate existing risks. For instance automation can eliminate some human errors but can introduce new and more catastrophic errors (Sarter and Woods, 1995) that can impact safety. There are many human factors health and safety implications that must be addressed in the early stages of the safety lifecycle. These issues include displays and controls, training, visual and audible alerts, communications, and information requirements (Dhillon, 2015). Neglecting human factors issues typically results in equipment safety and performance issues (Horberry et al., 2010).

Current Research

We are not aware of any active research external to NIOSH that is addressing the human factor health and safety implications with automated, semi-automated, and tele-remote control of mining machines. There was a human factors in mining study conducted in Australia where 508 incident/accident cases from across Queensland occurring from 2004-2008 were analyzed; however, the cases did not include automated, semi-automated, nor tele-remote equipment (Horrbery, et al, 2010).

Currently, human factors research is being conducted in the Human Factors Branch at NIOSH Pittsburgh; however, the research is not specifically focused on the human factors issues associated with automated, semi-automated, and tele-remote mining equipment.

NIOSH Comparative Advantage

NIOSH is well suited to conduct human factors research given the in-house expertise that resides in the Human Factors Branch at NIOSH Pittsburgh. There is a rich history in human factors research that dates back to the Bureau of Mines to the early 1990's. Numerous publications were written that include the seminal work "Human Factors in Mining" (Sanders and Peay, 1998) that addressed human factors in system design, human capabilites and limitations, human error, etc. More recent NIOSH Pittsburgh human factors research has several areas of specialization that include organizational human factors that pertains to sociotechnical systems, and organizational structures, policies and processes that comprise mining health and safety management systems (Wilmer and Haas, 2016)(Haas and Yorio, 2016). The main objective of current research is to identify and characterize health and safety performance practices – through worker-technology-management interactions – to provide guidance about risk management processes.

Human factors research requires human subject qualatative and quantative testing expertise which NIOSH has developed through years of research in the setting of a laboratory and in the field. Secondly, NIOSH has the unique facilities to conduct human factors research including the VisiLab, the human performance research laboratory, and the safety research and experimental coal mines. Active partnerships with labor unions and mining companies place NIOSH in a position to leverage resources and obtain relevant feedback and data from mine workers that will ultimately rely on this data for their safety. The human factors expertise and NIOSH facilities do not exist in the mining industry at a level that would enable the required research.

Outcomes and Risks

An expected outcome of this research will be improved human-centered system design, user interfaces, guidelines/best practices, interventions, and training materials that address the physical, behavioral, and cognitive responses to smart mine technologies. Automation is a smart mine technology that is critical because it changes the types of feedback that operators receive and the nature of their tasks.

Automation without human factors leads to new and more catastrophic failures (Nof, 2009).

Competencies

Competency	Level	In-house competency	Specific needs
Human subject testing	5	Yes	None
Behavior change theories	5	Yes	None
Surface/Underground mining methods	2-4	Yes	None
Automation technologies with respect to electrical, computer, and mechanical systems.	3-4	Yes	None
Cognitive processing theory motor planning, visual perception, attention, etc.)	3-5	Yes	None
Cognitive psychology	3-5	Yes	None

Facilities Needed

A facilities overview is provided in Appendix D.

- VisiLab (existing). No major VisiLab modifications are needed.
- Safety research coal mine and the experimental mine (existing). Major upgrades are needed and are already in progress.
- Surface and underground mines. Cooperating mine sites are needed which have been increasingly difficult to obtain.
- Human performance research laboratory (existing): No major laboratory modifications are needed.

3.6 Sensors

Definition

Sensor: a device that responds to a physical stimulus (such as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control). The term can refer to biologic, chemical and physical components used to monitor the environment, processes, equipment, and even personnel.

Background

The integration of sensors into industrial environments is a rapidly progressing field which has evolved tremendously through the miniaturization of electronics and increase in computing power. Their applications vary greatly based on the environment for which they are selected, however, the considerations for their integration are one and the same. Sensors are deployed for process monitoring/control and health/safety management.

Exposure assessment science is a discipline which is designed to identify and mitigate hazardous conditions in a given environment or task. In 2012, the National Research Council released a book titled *Exposure Science in the 21st Century: A Vision and a Strategy* which established a vision for methods and mechanisms for exposure assessments (NRC 2012). A major conclusion of the report was that new sensor methods and monitors will play a critical role in driving success in exposure sciences and exposure assessments.

Specific to mining, the extreme work conditions point to the need for technology to enhance mine worker situational awareness and ultimately improve health and safety. One approach to enhancing health and safety is to enable mine workers to manage these hazards by providing them with real-time data (environmental, physiological, and physical location data) obtained from wireless, wearable, smart sensor technologies deployed at the work area (Sammarco et al, 2007).

Regardless of the type of sensor, the process for designing, developing, and evaluating efficacy remains the same. The life-cycle for the development and application of sensors, as defined by the NIOSH Center for Direct Reading and Sensor Technologies (NCDRST), focuses on assessing the physical, operational and performance characteristics to ensure that the sensors are functional and achieve the intended task for which they are designed. The NCDRST was established to coordinate research and to develop recommendations on the use of 21st century technologies in occupational safety and health.

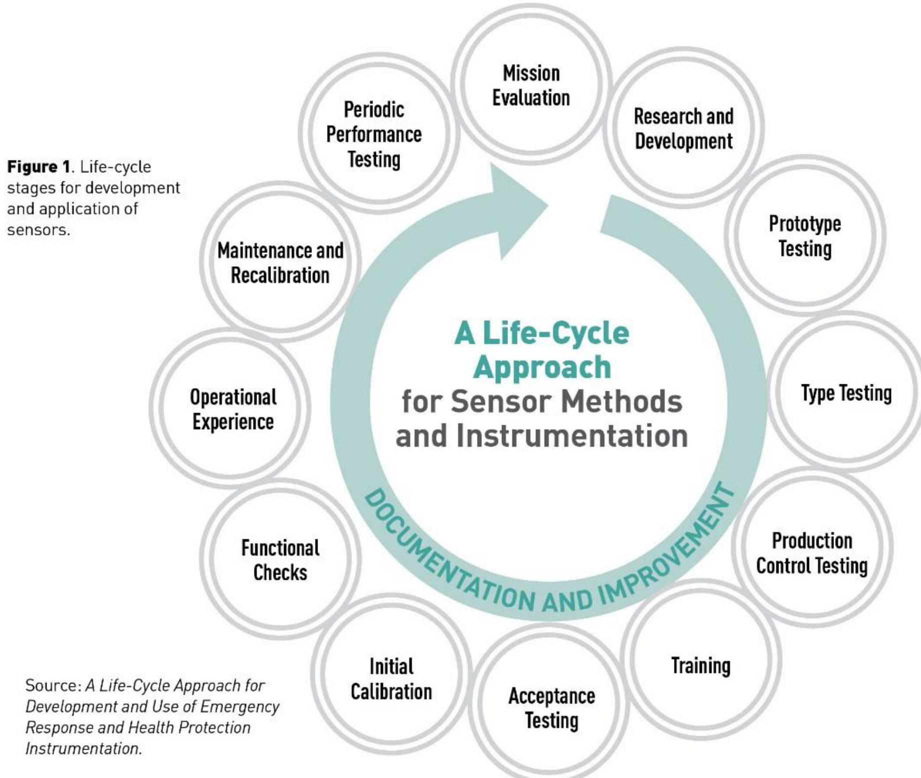

Figure 10 Life-cycle stages for development and application of sensors (Hoover and Cox, 2004)

Several types of sensors are currently in use within the mining industry and include:

- Acoustic, sound, vibration
- Chemical
- Electric current, electric potential, magnetic
- Environmental, moisture, humidity
- Flow, fluid velocity
- Navigation instruments
- Position, angle, displacement, distance, speed, acceleration
- Optical, light, imaging, photon

- Pressure, strain
- Force, density, level
- Thermal, heat, temperature
- Proximity

The NIOSH mining program has accumulated years of experience in all of these areas and is continuing to build a capacity to design, develop, evaluate, and integrate sensor technologies will be needed to further enhance health and safety as technologies continue to evolve.

Health and Safety Implications

The safety issues associated with the investigation of sensor technologies lies in the tasks which they are designed to accomplish. In mining, there are several critical components related to environmental, machine, and personnel monitoring applications.

- Environmental monitoring: Broadly defined as the environment in which the work takes place. Accumulation of toxic and combustible gasses can be precisely monitored to implement mitigation strategies. Ground movement can be assessed for signs of instability. Water inflow/outflow and remote area monitoring that mine workers infrequently visit can be monitored.
- Machine monitoring: Fleet management/machine component sensors can be monitored to prevent collisions between equipment, pinning and striking of personnel working in close proximity to equipment, and machine operating conditions/parameters that can directly contribute to machine maintenance/repair injuries and fatalities. Providing machine information to a miner on a personal device has a large potential to increase miner situational awareness.
- Mine worker monitoring: Mine location and physiological monitoring can locate mine workers during and after mine emergencies as well as identify fatigue and/or medical emergency situations.

Ensuring the proper design, calibration, and use are components of sensor integration that present safety issues relative to reliability of the system. In addition to the technical considerations for the design and development of sensors for mining, there exist other considerations such as evaluation of transferability potential from other industries and human factors.

The challenge in evaluating transferability from other industries lies in the adaptability to the new environment. Specifically, electromagnetic compatibility becomes a consideration due to the environmental conditions that exist in a mine that are not present in other industrial settings. An example of this is a sensor's susceptibility to electromagnetic interference due to operating frequencies and high voltage cables present in mines that may not be present in the sensor's "native" environment. Intrinsic safety is another issue of concern for coal mining applications.

Another consideration is evaluating the safety issues associated with the human factors in the design and use of the sensors. With the proliferation of sensors in mining environments there is a risk of cognitive overload related to sensor data or the usability of the sensors that can directly impact situational awareness.

These considerations relate to safety issues present in the integration of sensors in the mining environment and highlight some of the ongoing research being conducted within the mining program.

Current Research

Research in this area rapidly advances as technologies evolve. NIOSH is actively involved in sensor integration across the agency. Specifically, NIOSH is conducting research through the Division of Applied Research and Technology Exposure Assessment Cross Sector Program and the Direct Reading Exposure Assessment Methods (DREAM) initiative to investigate exposure assessment practices and produce direct reading sensor technologies to mitigate the challenges. These efforts focused on selection, validation, and integration of sensors. NIOSH continues to build upon that initiative to expand the DREAM program to address lessons learned, advances in technology, and stakeholder contributions.

The NIOSH Center for Direct Reading and Sensor Technologies is also actively involved in working with partners in industry, labor, trade associations, professional organizations, and academia to advance the development of sensors for occupational safety and health. Specifically, the center has focused on developing sensor relevant guidance documents and dissemination through seminars and published articles.

The Office of Mine Safety and Health Research (OMSHR) Broad Agency Announcement (BAA) contract program has funded a number of contracts for the development of sensors for mine environmental parameters. While the majority of these sensors remain in the prototype stage (primarily due to MSHA intrinsic safety requirements), they continue to advance the transfer of technology from other industries.

Several aspects of sensor integration focus on their design in terms of communications protocols, high capacity battery chemistries, computing power, and sensor sensitivities. NIOSH has worked in a number of these areas to enhance health and safety in mining. NIOSH has also been involved in the design and development of measurement tools and health and safety sensors designed to characterize exposure levels. Three examples of this are the personal dust monitors, proximity detection systems, and helmet cam. In conjunction with industry partners, NIOSH has enabled the industry to integrate these sensor technologies to address exposure to dust and toxic gases as well as protect miners working in close proximity to mining machines. These examples demonstrate research to practice as the finding from these research tasks have directly impacted the availability of commercially available tools used within the mining industry. Other sensor research includes exposure to noise, nitrogen dioxide, silica dust and DPM.

NIOSH Comparative Advantage

Due to its strong partnerships and experience with the design and development of sensor technologies, NIOSH is well suited to continue this work as it relates to developing mining specific sensors as well as evaluating sensors for potential transferability from other industries. A close working relationship with MSHA has enabled NIOSH to characterize challenges experienced by the mining industry and provide practical solutions for both short term and long-term needs. In addition to the technical design and integration of sensor technologies, NIOSH is also well suited to perform usability studies and field evaluations of sensor technologies as demonstrated in projects such as the, "Design of Proximity Systems for Underground Mobile Equipment" project, which also factors into affording the industry with a holistic approach to sensor integration. In doing so, NIOSH can contribute to extending exposure assessment research specific to mining industry as well as other industries with similar environmental conditions. Previous NIOSH work includes a wide variety of sensor topics such as documented in the publication "A Technology Review of Smart Sensors with Wireless Networks for Applications in Hazardous Work Environments" that addressed smart-wearable sensors, wireless sensor networks, and low-power embedded computing needed for smart sensors (Sammarco et al., 2007). This work included some potential to enable miners to safely manage the hazards produced by an ever-changing, unpredictable, dangerous work environment by providing them with real-time environmental and physiological data obtained from wireless, wearable, smart sensor technologies. Other sensor research for mining during the USBM era was geared toward machine automation where various sensor technologies (scanning lasers, ring-laser gyroscopes, near infrared sensors, etc.) were used to determine machine position and enable navigation of mobile mining equipment (Anderson, 1989; Sammarco, 1990; Schiffbauer, 1996).

Outcomes and Risks

The NIOSH Mining Program can directly contribute to the availability and accessibility of sensor technologies to enhance mining health and safety. By collaborating with industry stakeholders and effectively using current resources, NIOSH can develop improved monitoring techniques and guidance documents related to the integration, robustness with respect to environmental factors that include sources of interference, and usability of sensors and sensor networks. This may include sensor design and development, development of interoperability mechanisms, transferability, and validation of existing sensors such as those used in atmospheric monitoring systems, and machine safety interventions including proximity detection systems and personal dust monitors. Additionally, sensor data can be mined via big data analytics.

Although there are targeted efforts aimed at developing direct reading sensors in industrial settings, there is an inherent risk of ineffective transferability of sensors due to design and performance characteristics in sensors developed for use in environments different from conditions encountered in mining environments. A major risk is to focus resources on design and development of new sensors rather than forming partnerships to more rapidly develop practical solutions with a faster path towards commercialization.

Competencies

Competency	Level	In-house competency	Specific needs
Sensor design and development (biologic, chemical, physical sensors)	3-5	No	Expertise is needed at 3-5 competency level.
Communications protocols	3-5	Yes	None
Electromagnetic compatibility testing	3-5	Yes	None
Intrinsic safety	5	Yes	None

Human centered design	4-5	Yes	Expertise is needed at 4-5 competency level.
Situational awareness/risk perception	3-5	Yes	Expertise is needed at 3-5 competency level.

Facilities Needed

A facilities overview is provided in Appendix D.

- RF chambers (existing at both NIOSH Pittsburgh and Spokane). No major modifications are needed.
- Safety research coal mine and the experimental mine (existing). Major upgrades are needed and are already in progress.
- Although certified laboratories exist, NIOSH may benefit from exploring building laboratories dedicated to electromagnetic compatibility to evaluate sensors and sensor network components as well as other electronic devices used in the mining environment.

3.7 Systems Safety

Definitions

System safety: "the application of engineering and management principles, criteria and techniques to achieve acceptable risk, within the constraints of operational effectiveness, time and cost throughout all phases of the system life cycle" (DoD, 1997)

System: a collection of hardware, software, humans, and machines interconnected to perform desired functions.

Safety lifecycle: The necessary activities involved in the implementation of safety critical systems where the activities begin at the concept stage and cease after system decommissioning.

Background

System safety encompasses these subsystems (Fig. 11): software, hardware, the mine environment, the safety management system, and the human element ("liveware"). System safety is applied throughout the safety lifecycle (Fig. 12) that begins with system inception and concludes with system decommissioning. In essence, system safety identifies hazards and the associated safety-related risks, then controls unacceptable risks through design and/or procedures.

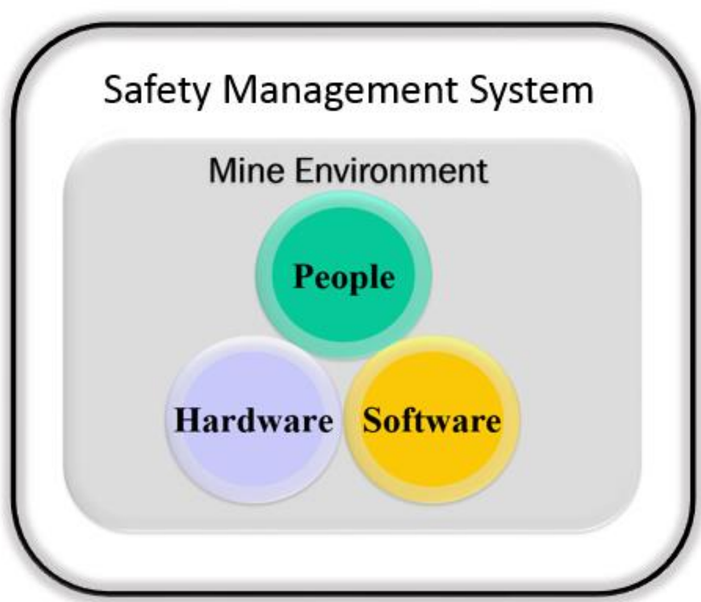

Figure 11: The interconnected subsystems that collectively comprise a system.

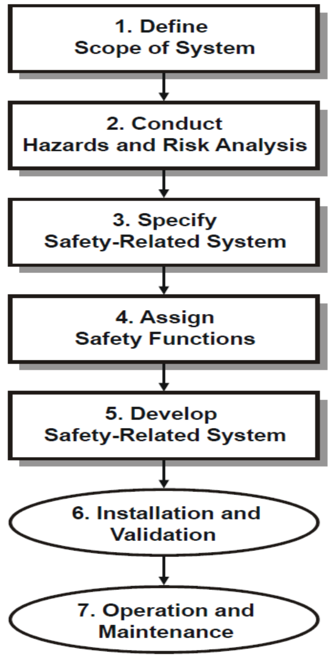

Figure 12. A simplified safety lifecycle that identifies the key lifecycle elements (Sammarco et al., 2001)

Health and Safety Implications

Escalating automation in mining is resulting in complex software-based mining systems that can eliminate or reduce some risks associated with traditional mining systems, potentially introduce new risks, and potentially increase some existing risks. Accidents involving mobile autonomous and semi-autonomous vehicles have occurred that include an autonomous haul truck colliding with a water truck and with a grader, and a blast hole autonomous drill rig reversing direction and colliding with a stationary blast hold drill rig while in remote control (DPM, 2014). Some of the contributory factors included users remotely overriding safety systems and collision detection systems that were not included in the design or that only worked in certain conditions of forward motion (DPM, 2014).

The complexity of these autonomous, semi-autonomous, and tele-remote mining systems makes it more likely for design errors, human errors, system failure, and unplanned interactions among humans and the mining environment. Secondly, robotics and automation systems exhibit a high degree of coupling and rapid interaction among the subsystems such that these interactions and the state of the system are not discernable by humans (Perrow, 1984). Thus, hazard and risk analysis techniques should not be applied to only one subsystem such as hardware; but must be applied to all subsystems. Thirdly, traditional hazard and risk analysis techniques were initially developed for relatively simple electromechanical systems; however, these traditional techniques have very limited usefulness for the changing nature of accidents associated with robotics and automation (Leveson, 2011). Thus, more effective system safety hazard and risk analysis are needed for robotic and automated systems in mining.

Secondly, there are changes in the remote control of mining machines. Historically, remote control has been in the relatively simple mode of line-of-sight control where the miner is located a relatively short distance away from the mining machine. Fatalities have resulted even though this is simple remote control. The trends today are for an increasing use of complex tele-remote control where the operator can be located miles away from a mining machine. There are various degrees of tele-remote where the operators have:

- full control of a single machine;
- collaborative control of a semi-autonomous machine;
- supervisory control and monitoring of multiple semi-autonomous machines or fully autonomous machines such as encountered in monitoring and controlling a dispatching system for multiple surface haulage trucks.

These more complex types of tele-remote control can create new hazards especially concerning collisions with people and other machines or equipment. The existing standard (AS/NZS 4240.1, 2009) does not address the health and safety implications concerning the complexities of tele-remote.

Lastly, the mining industry is quickly moving towards the new technologies of a Smart Mine that capitalizes on the internet of things (IoT) to increase operational efficiency and reduce downtime. For the forecast period 2015-2020, the global smart mining market is anticipated to increase at a compound annual growth rate of 14.5%, and create US$ 13 Bn in revenues (Future Market Insights, 2017). Again, the introduction of these new technologies have the potential to create new risks or exacerbate existing risks thus more effective system safety hazard and risk analyses are needed.

Current Research

There appears to be no active mining system safety research external to NIOSH. NIOSH has conducted system safety research but this research focused on the application of traditional hazard and risk techniques for mining systems that used software control (Sammarco et.al. 2005). This research did not address the complexity of automated mining systems that are now rapidly emerging in mining nor did it address the Internet of things.

NIOSH Comparative Advantage

NIOSH has limited expertise in system safety. However, it does possess extensive expertise in areas that directly relate to the general topic area. Specifically, NIOSH researchers have collectively acquired decades of experience in fields related to software development, hardware development and integration, a wide range of mining methods, development and implementation of health and safety management systems, and human factors/behavioral science. NIOSH is well suited to conduct this research given the expertise in conducting worker safety research including projects related to intelligent proximity detection, intelligent lock out/tag out, and system safety of programmable electronic mining systems. While NIOSH does need to further develop systems engineering competencies to investigate program risk management, it does possess the comparative advantage of a strong foundation for this area of research. NIOSH can also leverage recent advancements and collaborations/partnerships with mine operators, actively looking to enhance safety, to position itself to continue building upon established work. Lastly, NIOSH does have experience with mining HSMS's (Willmer and Haas, 2016) (Haas and Yorio, 2016) that could serve as a critical foundation for HSMS's specific to robotic and automated systems in mining.

Outcomes and Risks

This research would result in safety management systems and systematic hazard and risk analysis techniques specifically geared for the technologies of mining automation and those technologies associated with a Smart Mine.

The research would be used by the industry in the design, operation, maintenance and management of mine automation equipment and Smart Mines. The research outputs would include best practice guidance documents that could be used by the industry and the outputs could serve as a basis for new standards or updating of existing standards. As an example, the Australian/New Zealand standard AS/NZS 4240.1 for remote control of mining equipment is heavily based upon NIOSH best practice recommendation guidelines (AS/NZS 4240.1, 2009). It would be likely that the knowledge gained could be generalized to other industries.

Competencies

Competency	**Level**	**In-house competency**	**Specific needs**
System Safety	5	Yes	Expertise is needed at 5 competency level.
Surface/Underground mining methods	2-5	Yes	None
Automation technologies (with respect to electrical, computer, and mechanical systems)	3-4	Yes	Expertise is needed at 3-4 competency level.

Hazard/Risk analysis	4-5	Yes	Expertise is needed at 4-5 competency level.
Human centered design	4-5	Yes	None
Mine regulations	3-5	Yes	None
Mine equipment operation and design	3-5	Yes	None
Ergonomics	3-5	Yes	None

Facilities Needed

A facilities overview is provided in Appendix D.

- Safety research coal mine and the experimental mine (existing). Major upgrades are needed and are already in progress.
- Human performance research laboratory (existing): No major laboratory modifications are needed.

4.0 Recommendations

4.1 Situational awareness

1. **(PRIORITY)** In-house expertise in situational awareness should be developed in the areas of SA requirements analysis, SA modeling, SA-oriented design, and SA measurement, especially in the context of automation applications, through training. Alternately the expertise could be gained through hire or research contract.
2. **(PRIORITY)** NIOSH should partner with the Global Mining Standards & Guidelines Group (GMSG) which has a SA workgroup.

4.2 Automation

1. **(PRIORITY)** NIOSH Mining should maintain a working relationship with the NIOSH Center for Occupational Robotics Research for the purposes of sharing information and collaboration on common research areas. NIOSH Mining should maintain a working relationship with the NIOSH Center for Motor Vehicle Safety for the purposes of sharing information and collaboration on common research areas.
2. **(PRIORITY)** NIOSH should become involved (member) with standards and industry organizations developing guidelines for implementing automated and semi-automated equipment immediately to ensure these efforts are informed by current safety research and to aid in dissemination to US mines.

4.3 Data analytics

1. NIOSH should become knowledgeable on the industry trends on data analytics for occupational health and safety, including resource requirements, tools available, progress on system developments, and NIOSH role. NIOSH HELD (Anne Foreman PI) just had a FY18 NORA project funded titled "Improving Occupational Safety with Big Data Mining and Analytics" that should be followed.

4.4 Human factors

1. **(PRIORITY)** In-house expertise in man/machine interfaces, especially in the context of automation, needs to be developed via training during FY18, or this expertise should be hired given there will likely be an ongoing need for this expertise.

4.5 Sensors

1. Establish a subproject or task within NIOSH Mining to research and consolidate the sensors currently utilized in mining under the categories of permissible and non-permissible among other criteria. Determine the areas

that are lacking or require further development of sensor technology or more appropriately require MSHA approval.

2. NIOSH Mining should maintain a working relationship with the NIOSH Center for Direct Reading and Sensor Technologies for the purposes of sharing information and collaboration on common research areas.
3. NIOSH should develop the Safety Research Coal Mine into a testbed and research facility for advanced sensor, wearables sensors, personal display devices, and big data monitoring to increase miner situational awareness.

4.6 System safety

1. In-house expertise in system safety needs to be developed via training, or this expertise could be hired given there will likely be an ongoing need for this expertise.

4.7 General

1. **(PRIORITY)** Submit a Request for Information in the Federal Register that provides the opportunity for interested individuals and organizations to identify public and private actions that are actively involved in smart mines and mining automation in order for NIOSH to determine future research direction and potential collaborators.
2. **(PRIORITY)** An electronic information sharing system and process needs to be established to capture smart mine technologies that are being developed and implemented. This includes information from NIOSH researchers traveling to mine sites, equipment manufacturers, universities, and relevant conferences.
3. **(PRIORITY)** NIOSH Mining should partner with universities and other research organizations to more quickly gain expertise in smart mining technologies and to more effectively use our resources. The Carnegie Mellon University Robotics Group and the West Virginia University Mechanical Engineering Robotics Group are ideal candidates. NIOSH Mining should partner with OEM's and universities that have expertise in robotics and automation. One example is the Carnegie Mellon University National Robotics Engineering Center.
4. The Mine of the Future Workgroup should be involved in developing a plan to implement the next steps for NIOSH Mining.
5. **(PRIORITY)** NIOSH Mining should collaborate with mining companies with plans to implement automation and smart mine technologies. Barrick Gold (Mines in Nevada) and Hecla (Mines in Idaho and Alaska) have expressed interest in working with NIOSH as they explore advanced technology and automation for their mines.

5.0 Definitions:

- **Automated mining** – removal of human labor from the mining process. This refers to two types of technology, the first deal with process and software automation, and the second refers to applying robotic hardware and software technology that convert mining vehicles or equipment into autonomous mining units.
- **Automation** - automation traditionally refers to a process or piece of equipment that operates automatically, usually under some level of computer control.
- **Data Analytics** - the process of extracting information from raw data using specialized statistical computer systems.
- **Disruptive technology** - any enhanced or completely new technology that replaces and disrupts an existing technology, rendering it obsolete. It is designed to succeed similar technology that is already in use. Disruptive technology applies to hardware, software, networks and combined technologies.
- **Full automation** – autonomous control of a vehicle. Robotic components manage all critical vehicle functions including ignition, steering, transmission, acceleration, braking, and implement control without the need for operator intervention.
- **Human factors** - the systematic application of relevant human characteristics, abilities, expectations, and behaviors to the design and operation of tools, machines, procedures, and facilities.
- **Operator assist** – refers to partly automated control of vehicles. Only some functions are automated and operator intervention is needed.
- **Remote control** – control of vehicles with a handheld remote control. An operator stands in line-of-sight and uses the remote control to perform the normal vehicle functions.
- **Robotics** - robotics is related to automation and typically refers to a machine that automatically performs a task or process in place of a human.
- **Safety lifecycle** - the necessary activities involved in the implementation of safety critical systems where the activities begin at the concept stage and cease after system decommissioning.
- **Sensor** - a device that responds to a physical stimulus (such as heat, light, sound, pressure, magnetism, or a particular motion) and transmits a resulting impulse (as for measurement or operating a control).
- **Situational Awareness -** the perception of elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future.

- **Smart mine** - the use of disruptive technologies associated with automation and robotics, wireless communications, smart sensors, wearable platforms, augmentation of reality, interconnectivity afforded by the internet of things technologies and data analytics.
- **System** - a collection of hardware, software, humans, and machines interconnected to perform desired functions.
- **System safety** - the application of engineering and management principles, criteria and techniques to achieve acceptable risk, within the constraints of operational effectiveness, time and cost throughout all phases of the system life cycle.
- **Tele-operated control** – control of vehicles by an operator at a remote location with the use of cameras and/or sensors. This allows the operator to be moved from the mining location and control the vehicle from a more protected environment.

6.0 References:

AS/NZS 4240.1 (2009). Remote Control Systems for Mining Equipment. Part One: Design, Construction, Testing, Installation and Commissioning. Standards Australia and Standards New Zealand

Anderson, Donna (1989). Position and heading determination of a continuous mining machine using an angular position-sensing system. US Bureau of Mines IC 9222

Bellamy D., Pravica, L. (2011). Assessing the impact of driverless haul trucks in Australian surface mining, Resources Policy, Volume 36, Issue 2, June 2011, Pages 149-158.

BMI Research (2015). "Smart Mining": The Key Areas of Innovation.

Cosbey, A.; Mann, H.; Maennling, N.; Toledano, P.; Geipel, J.; Brauch, M. (2016). Mining a Mirage? Reassessing the shared-value paradigm in light of the technological advances in the mining sector. International Institute for Sustainable Development

Cullen, Brendon; Fox, Brian (2016). The Growing Potential for Fully Autonomous Mines. OEM Off-Highway, September 2016.

Department of Mines and Petroleum (DPM) (2014). "Seeking Safe Mobile Autonomous Equipment Systems ". Government of Western Australia. Mine Safety Bulletin Number 110 http://www.dmp.wa.gov.au/Documents/Safety/SRS-Publications-Mining_and_Explorations-Safety_Bulletin_110.pdf

Department of Mines and Petroleum (DPM) (2015). Safe mobile autonomous mining in Western Australia – code of practice: Resources Safety, Department of Mines and Petroleum, Western Australia, 30 pp.

Dhillon, B.S. (2015). Robot System Reliability and Safety: a Modern Approach. CRC press

Department of Defense (DoD) (1997). Standard Practice for System Safety. (MIL-STD-882D). U.S. Department of Defense

EMESRT (2016). Vehicle Interaction Systems. Earth Moving Equipment Safety Round Table Performance Requirement PR-5A.

Endsley, M. R. (1995). Toward a theory of situational awareness in dynamic systems. *Human Factors, 37*(1), 32-64.

Endsley, M., Jones, D. (2013). Designing situational awareness: an approach to user-centered design. Boca Raton, FL, CRC Press.

Fuller, R.G. (2014). The impact of non-technical issues on decision-making by coal mining incident management teams. University of Queensland. Dissertation

Future Market Insights (2017). Smart mining market: digital revolution to transform the mining sector: global industry analysis and opportunity assessment, 2015 to 2020.
http://www.futuremarketinsights.com/reports/smart-mining-market
Accessed March 2017

Global Mining Standards & Guidelines Group (GMSG) (2017). "Situational Awareness" Web Page
http://www.globalminingstandards.org/working_group_categories/situation-awareness-sa/ Accessed: March 2017

Haas EJ, Yorio P (2016). Exploring the state of health and safety management system performance measurement in mining organizations. Saf Sci. 2016 Mar; 83:48-58.

Hoover MD, Cox M (2004). A life-cycle approach for development and use of emergency response and health protection instrumentation; chapter in Public protection from nuclear, chemical, and biological terrorism. A. Brodsky, R. H. Johnson Jr, R. E. Goans, eds. Madison, WI: Medical Physics Publishing, 2004 Jul; :317-324

Horberry T, Burgess-Limerick R, Steiner L. (2010). Human factors for the design, operation, and maintenance of mining equipment. New York: CRC Press 2010.

ISO 17757:2017 Earth-moving machinery and mining -- Autonomous and semi-autonomous machine system safety; standard, 36 pp.

ISO/AWI 21815 Earth-moving machinery -- Collision awareness and avoidance; safety standard under development.

Jensen, Sara (2016). The Growing Potential for Fully Autonomous Mines. OEM Off-Highway. September 9, 2016;

https://www.oemoffhighway.com/electronics/smart-systems/automated-systems/article/12243110/autonomous-mining-equipment

Leveson, N. (2011). Engineering a Safer World: Systems Thinking Applied to Safety. The MIT press

Lopez-Pacheco, A. (2017). The Automation Revolution – What is the best way into the automated future? *CIM Magazine*, Vol 12, No. 5.

Lynas, D, and Horberry, T. (2011). Human factors issues with automated mining equipment. *The Ergonomics Open Journal,* 2011, *4,* (Suppl. 2-M3), 74-80.

NIOSH, 2012. Components for Evaluation of Direct Reading Monitors for Gases and Vapors. DHHS (NIOSH) Publication Number 2012-162, July 2012

Nof, S. (Editor) (2009). Springer Handbook of Automation. Chapter 25 " Human Factors in Automation Design".

Norton, S. (2017) Underground mining efforts shift Rio Tinto's innovation approach. Wall Street Journal, June 7, 2017. https://blogs.wsj.com/cio/2017/06/07/underground-mining-efforts-shift-rio-tintos-innovation-approach/

NRC (2012). *Exposure Science in the 21st Century: A Vision and a Strategy*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13507.

NRC (2013). Improving Self-Escape from Underground Coal Mines. Washington, D.C., The National Academies Press.

Onal, E.; Craddock, C.; Endsley, M. (2012). Surface Mining Association for Research and Technology "SMART Shovel" Project Overview. SA Technologies, Inc.

Paraszczaka, J., Gustafsonb, A., Schunnesson, H. (2015). Technical and operational aspects of autonomous LHD application in metal mines. International Journal of Mining, Reclamation and Environment, Vol.29, No.5, 391–403.

Perrow, C. (1984). Normal Accidents: Living with High-Risk Technologies. Basic Books

Peterson, D., LaTourrette, T., Bartis, J. (2001). New forces at work in the mining industry: Industry views of critical technologies. RAND.

PR Newswire, 2017. “Smart Mining Market by Hardware Component, System & Solution, Service - Global Opportunity Analysis and Industry Forecast, 2014 – 2022.

Rio Tinto (2013). Rio Tinto innovation. Presentation to Austmine, Perth, Western Australia.

Rio Tinto (2016). “Driving productivity in the Pilbara”, Western Australia’s remote Pilbara region is dotted with three-storey high trucks driving themselves around the red dirt landscape, webpage last updated on June 1, 2016, http://www.riotinto.com/ourcommitment/spotlight-18130_18328.aspx

SA Technologies (2012). MSGC Shovel Project Final Report including User Testing Results. Dec. 2012

Sammarco, J. (1990). Mining machine orientation control based on inertial, gravitational, and magnetic sensors. US Bureau of Mines IC 9326.

Sammarco, J.; Fisher T.; Welsh J.; Pazuchanics. M. (2001). Programmable electronic mining systems: best practice recommendations (in nine parts). Part 1: 1.0 Introduction. National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2001–132, IC 9456.

Sammarco, J; Mowery, G.; Fries, E.; Fisher, T.; Flynt, J.; Welsh, J (2005) Programmable electronic mining systems: best practice recommendations (in nine parts). National Institute for Occupational Safety and Health Informational Circulars

Sammarco J, Padock R, Fries EF, Karra VK. (2007) *Technology Review of Smart Sensors with Wireless Networks for Applications in Hazardous Work Environments*. National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2007-114, Information Circular 9496, 2007 Apr:1-49

Sanders, M.S., Peay (1988). J.M., Human Factors in Mining. Bureau of Mines Information Circular, 1988(9182)

Sarter NB, Woods, DD. (1995). How in the world did we ever get in that mode? Mode error and awareness in supervisory control. Hum Factors. 1995; 37(1): 5-19.

Schiffbauer, William (1996). Navigation and control of continuous mining systems for coal mining. IEEE Industry Applications Society Thirty-First IAS Annual Meeting.

Staff (2016). Smart Mining Market: Digital Revolution to Transform the Mining Sector: Global Industry Analysis and Opportunity Assessment, 2015-2020. Future Market Insights Inc., October 2016, 100pp.

Sheridan, T. (2016). Human-Robot Interaction: Status and Challenges. Human Factors. Vol. 58, No. 4

Wagner, Gregory R. (2014). "Can Predictive Analytics Help Reduce Workplace Risk?", NIOSH Science Blog, Posted on October 2, 2014 https://blogs.cdc.gov/niosh-science-blog/2014/10/02/pa/

Willmer DR; Haas EJ (2016). Managing health and safety risks: Implications for tailoring health and safety management system practices. Trans Soc Min Metall Explor Inc. 2016;340(1):100-103. doi: 10.19150/trans.7333.

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Appendix A: Mines Using Smart Mine Technologies

AUSTRALIA:

MINING COMPANY: Rio Tinto
MINE: Argyle Mine
MINE TYPE: Underground block caving
ORE: Diamond
LOCATION: East Kimberley region of Western Australia
TECHNOLOGY:
Automation system

MINING COMPANY: Fortescue
MINE: Firetail Mine/Kings Valley Mines
ORE: Iron Ore
MINE TYPE: Surface Open Pit
LOCATION: Pilbara Region, Western Australia
TECHNOLOGY:
Autonomous haulage – 45 CAT 793F trucks

MINING COMPANY: BHP Billiton
MINE:
ORE: Iron Ore
MINE TYPE: Surface open pit
LOCATION: Philbara Region, Western Australia
TECHNOLOGY:
Fully autonomous truck fleet. All blast hole drilling done autonomously by end of 2017.

MINING COMPANY: BHP Billiton
MINE: Broadmeadow Mine
ORE: Coal
MINE TYPE: Underground
LOCATION: Central Queensland Australia
TECHNOLOGY:
Remotely operated longwall shearer and longwall system.

MINING COMPANY: Mandalay Resources
MINE: Costerfield Mine
ORE: Gold-antimony
MINE TYPE: Underground, cemented rock fill blast-hole stope method
LOCATION: 100 km NW Melbourne, Victoria, Australia
TECHNOLOGY:
RCT tele-operated Sandvik LH Loaders from underground control station

MINING COMPANY: CMOC International
MINE: Northparkes Mine

ORE: Copper and gold
MINE TYPE: Underground block cave mine, sublevel cave
LOCATION: Parkes, New South Wales, Australia
TECHNOLOGY:
100% automated loaders, they run themselves in moving and dumping the ore.
Controlled from surface control room, 1 operator controls 3 Sandvik autonomous systems.

MINING COMPANY: Rio Tinto
MINE: West Angelas Mine
ORE: Iron Ore
MINE TYPE: Surface Open Pit
LOCATION: Pilbara Region, Western Australia
TECHNOLOGY:
Fully integrated, automated mining. Autonomous Haulage System (AHS) using Komatsu haul trucks (71). Fully autonomous train. Seven fully Autonomous Drill Systems (ADS) to drill production blast holes (remote operator operates multiple drill rigs). Drones are being trialed to measure stockpiles and assist with environmental and maintenance activities. Integrated data management, analysis from operations center in Perth (1300 km away). RTVis software interprets datasets, creates 30 displays. 15 mines, 31 pits, 4 port terminals, and 1600 km rail managed from operations center in Perth.

BRAZIL:

MINING COMPANY: Vale
MINE: Carajas Serra Sul (S11D) Mine
MINE TYPE: Surface open pit
ORE: Iron Ore
LOCATION: State of Para in Northern Brazil
TECHNOLOGY:
Automated and completely truck-less

CANADA:

MINING COMPANY: ArcelorMittal Mines Canada
MINE: Mont-Wright
MINE TYPE: Surface open pit
ORE: Iron Ore
LOCATION: Fermont, Quebec Canada
TECHNOLOGY:
Partnered with OSIsoft, LLC for mine to port operational intelligence
Use latest data analytics tools

MINING COMPANY: Barrick Gold & Teck Cominco
MINE: Williams Mine
MINE TYPE: Underground (longhole stoping with paste backfill) & Open pit
ORE: Gold
LOCATION: Hemlo Property Area, Marathon, Ontario, Canada
TECHNOLOGY:

Autonomous haul trucks

MINING COMPANY: Hecla Mining Company
MINE: Casa Berardi Mine
MINE TYPE: Underground
ORE: Gold
LOCATION: North of La Sarre, Quebec
TECHNOLOGY:
Automated loading and hoisting of ore, tele-remote rock breaking, semi-automation of face drilling and longhole blasthole drilling, autonomous truck haulage, automated traffic control, mine environment and process monitoring.

CHILE:

MINING COMPANY: Codelco
MINE: El Teniente Mine
ORE: Copper
MINE TYPE: Underground
LOCATION: 80 km to the south of Santiago, Chile
TECHNOLOGY:
Developing the New Mine Level that will be fully automated and mining, processing and transport will be managed with remote control technology.

SOUTH AFRICA:

MINING COMPANY: Petra Diamonds
MINE: Finsch Mine
MINE TYPE: Underground block-caving system
ORE: Diamond
LOCATION: Near Lime Acres, 165km west of Kimberley in the Northern Cape province, South Africa
TECHNOLOGY:
Automated haulage and transport systems.

MINING COMPANY: Anglo-American
MINE: Twickenham Mine
ORE: Platinum
MINE TYPE: Underground
LOCATION: South Africa
TECHNOLOGY:
Continuous hard rock mining. FuturesMart Mining includes: Intelligent connected mining, Partner with Atlas Copco, Rapid Mine Development System (RMDS), Advanced drilling and cutting, Develop low profile tunnels in hardrock.

MINING COMPANY: Anglo American
MINE: New Vaal collieries
MINE TYPE: Open pit
ORE: Coal

LOCATION: South of Vereeniging, South Africa
TECHNOLOGY:
Automated dozer.

SWEDEN:

MINING COMPANY: Boliden
MINE: Garpenberg Mine
MINE TYPE: Underground
ORE: Zinc, and complex ores containing lead, silver, copper and gold
LOCATION: Hedemora municipality, Sweden
TECHNOLOGY:
Automation with partners Volvo, Ericsson, Atlas Copco, Sandvik and ABB.

MINING COMPANY: Boliden
MINE: Kankberg Mine
MINE TYPE: Underground
ORE: Gold and rare earth metal tellurium
LOCATION: Västerbotten in northern Sweden
TECHNOLOGY:
Installed new 5G radio infrastructure from Ericsson. Industry pilot and research collaboration between Ericsson, ABB, Boliden, SICS Swedish ICT, TeliaSonera, Volvo Construction Equipment and Luleå University of Technology. Volvo testing remote-controlled wheel loader.

MINING COMPANY: Boliden
MINE: Kristineberg Mine
MINE TYPE: Underground
ORE: Zinc, copper, lead, gold and silver
LOCATION: Västerbotten in northern Sweden
TECHNOLOGY:
Volvo testing driverless truck, also ventilation automation. Partner of the European consortium on Sustainable Intelligent Mining Systems.

MINING COMPANY: Luossavaara-Kiirunavaara AB
MINE: Kiruna Mine
MINE TYPE: Underground
ORE: Iron Ore
LOCATION: Kiruna, Sweden
TECHNOLOGY:
Automated drilling and load-haul-dump. Caterpillar joint venture with Lateral Dynamics developed MINEGEM Automation System for vehicle operation.

MINING COMPANY: Luossavaara-Kiirunavaara AB
MINE: Malmberget Mine
MINE TYPE: Underground
ORE: Iron Ore
LOCATION: Malmberget, Sweden

TECHNOLOGY:
Automated drilling and load-haul-dump. Caterpillar joint venture with Lateral Dynamics developed MINEGEM Automation System for vehicle operation.

UNITED STATES:

MINING COMPANY: Barrick Gold
MINE: Cortez Mine
MINE TYPE: Surface Open Pit & Underground underhand cut & fill
ORE: Gold
LOCATION: Elko, Nevada
TECHNOLOGY:
Automation and data integration coming. Doing a pilot study now.
Pilot with Hexagon Mining's SAFEmine collision avoidance and vehicle tracking information system.

MINING COMPANY: Arch Coal
MINE: Leer Mine
MINE TYPE: Underground
ORE: Coal
LOCATION: Grafton, WV
TECHNOLOGY:
Stockpile safety system, remote-controlled dozer for stockpile

MINING COMPANY: Hecla Mining Company
MINE: Lucky Friday Mine
MINE TYPE: Deep underground, ramp access, cut and fill
ORE: Silver
LOCATION: Shoshone County, Mullan, Idaho
TECHNOLOGY:
Atlas Copco hard rock mobile vein mining machine is being manufactured, to be tele-operated. Will use automated loaders or trucks behind the miner to transport ore. Battery-powered LHDs, wireless sensors for environment, seismic and deformation monitoring.

MINING COMPANY: Newmont
MINE:
ORE: Gold, copper, silver
MINE TYPE: Surface and Underground
LOCATION: Northern Nevada
TECHNOLOGY:
Semi-autonomous LHDs, CAT MineStar Command

MINING COMPANY: Westmoreland Coal
MINE: San Juan Mine
MINE TYPE: Underground
ORE: Coal
LOCATION: Farmington, New Mexico
TECHNOLOGY:

Longwall automation, Joy System, Mimic cut

MINING COMPANY: Arch Coal
MINE: Thunder Basin Coal
MINE TYPE: Surface
ORE: Coal
LOCATION: Powder River Basin, Campbell County, Wright, Wyoming
TECHNOLOGY:
Semi-autonomous dozer system

MINING COMPANY: Alliance Resources
MINE: Tunnel Ridge Mine
MINE Type: Underground
ORE: Coal
LOCATION: Ohio County, West Virginia
TECHNOLOGY:
Longwall automation, Caterpillar IMS, remote control location

MINING COMPANY: Alliance Resource
MINE: White Oak Mine No. 1
MINE TYPE: Underground
ORE: Coal
LOCATION: Hamilton County, McLeansboro, Illinois
TECHNOLOGY:
Longwall automation, Caterpillar IMS, remote control location

MINING COMPANY: Hecla Mining Company
MINE: Green's Creek Mine
MINE TYPE: Underground, tunneling & cement backfiling
ORE: Silver
LOCATION: Admiralty Island, Alaska
TECHNOLOGY:
Monitoring and control – Fiber optic cable throughout, Wifi hotspots. Wireless data collection goes to surface station for display. RFID tags on equipment and cap lamps for tracking, Collision avoidance, Real-time monitoring - CO, NO2, O2, SO2, DPM, Cameras, Data display remotely – Tablets, VOIP phones, Mine cloud storage – maps, drawings, manuals, inspection records, Electronic blasting, Geotechnical monitoring, Equipment diagnostics. Sandvik AutoMine Lite automated loading technology is being used.

MINING COMPANY: Rio Tinto (joint venture with BHP Billiton)
MINE: Resolution Mine
ORE: Copper
MINE TYPE: Underground
LOCATION: Superior, Arizona
TECHNOLOGY:
Deep mine, 7000 feet deep, 175 ^{o}F. Plans to install tens of thousands of electronic sensors, autonomous vehicles, complex ventilation system, data analytics. Use CaveCAD (Rio Tinto proprietary underground mining information management system, SAP SE (equipment information system).

Appendix B: Landscape Diagram - Mining of the Future

"MINING of the FUTURE" LANDSCAPE

Associations

- Industrial Minerals Association – North America (IMA-NA) - http://www.ima-na.org/
- National Mining Association (NMA) - http://nma.org/
- National Stone, Sand, and Gravel Association (NSSGA) - http://www.nssga.org/

Big Data

- IBM - https://www.ibm.com/us-en/
- MineWare - http://www.mineware.com/news/
- OSIsoft - http://www.osisoft.com/solutions/industry-solutions/metals-mining-and-metallurgy/
- Uptake - http://www.caterpillar.com/en/news/corporate-press-releases/h/caterpillar-and-uptake-to-create-analytics-solutions.html

Equipment Manufacturer

- Atlas Copco - http://www.atlascopcogroup.com/en

- Caterpillar - http://www.cat.com/en_US/campaigns/awareness/built-for-it-en-us/smart-iron.html?utm_source=bing&utm_medium=cpc&utm_campaign=BING%20-%20Exact%20-%20Caterpillar%20Brand%20-%20M%20-%20US&utm_term=caterpillar&utm_content=General
- J.H. Fletcher - http://www.jhfletcher.com/
- Hitachi - http://www.hitachi.com/businesses/category/construction_machinery/index.html
- Joy Global (Purchased by Komatsu and operated as a division) - https://mining.komatsu/
- Komatsu - http://www.komatsuamerica.com/innovation
- Sandvik - https://mining.sandvik.com/en
- Volvo - http://www.mining-technology.com/contractors/transportation/volvo-construction-equipment/

Government

- Army Research Laboratory (ARL) - http://www.arl.army.mil/www/default.cfm
- Commonwealth Scientific and Industrial Research Organization, Australian Government (CSIRO) - https://www.csiro.au/en/Research/Mining-manufacturing
- Council for Scientific and Industrial Research (CSIR) - https://csir.co.za/
- Defense Advanced Projects Research Agency (DARPA) – http://www.darpa.mil/
- Government of Western Australia, Department of Mines and Petroleum - http://dmp.wa.gov.au/
- Mine Safety and Health Administration (MSHA) – https://www.msha.gov/
- National Institute for Occupational Safety and Health (NIOSH) – https://www.cdc.gov/niosh/mining/index.html
- National Institute of Standards and Technology (NIST) – https://www.nist.gov/
- National Science Foundation (NSF) - https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503641
- SNL (Sandia National Laboratories) – http://www.sandia.gov/research/robotics/unique_mobility/gemini-scout.html

Labor

- Construction, Forestry, Mining and Energy Union (CFMEU) - https://me.cfmeu.org.au/
- International Union of Operating Engineers (IUOE) - http://www.iuoe.org/
- United Mine Workers of America (UMWA) - http://umwa.org/
- United Steel Workers (USW) - http://www.usw.org/

Mining Company

- Anglo American - http://www.angloamerican.com/
- Arch Coal - http://www.archcoal.com/
- Barrick Gold - http://barrick.com/

- BHP Billiton - http://www.bhpbilliton.com/
- CMOC International - http://www.cmocinternational.com/
- Fortescue Metals Group - http://fmgl.com.au/
- Hecla Mining Company - http://www.hecla-mining.com/
- Mandalay Resources - http://www.mandalayresources.com/
- Newmont Mining Corporation - http://www.newmont.com/home/default.aspx
- Rio Tinto - http://www.riotinto.com/australia/pilbara/mine-of-the-future-9603.aspx

Private Research

- Adaptive ADAS to support incapacitated drivers Mitigate Effectively risks through tailor made HMI under automation (ADAS&ME) - http://www.adasandme.com/
- Canada Mining Innovation Council - http://cmic-ccim.org/
- Mining3 - https://www.mining3.com/
- National Robotics Engineering Center (NREC) - http://www.nrec.ri.cmu.edu/
- Sustainable Intelligent Mining Systems - http://www.simsmining.eu/

Sensors & Technology

- Autonomous Solutions Inc. (ASI) - https://www.asirobots.com/
- General Electric (GE) - https://www.ge.com/digital/products/mine-performance
- Hard-Line - http://www.hard-line.com/en/
- Hexagon Mining - http://hexagonmining.com/
- Mobilaris - http://www.mobilaris.se/solutions/mining-and-industrial-intelligence
- Modular Mining Systems Inc. - http://www.modularmining.com/
- Newtrax technologies Inc. - http://www.newtrax.com/
- Penguin Automation Systems - http://www.miningglobal.com/tech/1224/Penguin-ASI-Takes-Mining-Automation-to-the-Next-Level
- PBE Group - http://pbegrp.com/
- Preco Electronics - http://preco.com/
- Remote Control Technologies (RCT) - http://rct-global.com/
- Scania - https://www.scania.com/global/en/global/scania-solutions/industry/mining.html
- Strata Worldwide - http://www.strataworldwide.com/
- Velodyne LIDAR - http://velodynelidar.com/

Standards

- International Electrotechnical Commission (IEC) - http://www.iec.ch/functionalsafety/
- International Organization for Standardization (ISO) - https://www.iso.org/home.html
- Standards Australia - http://www.standards.org.au/Pages/default.aspx

Universities

- University of Arizona - http://www.mge.arizona.edu/
- Carnegie Mellon University - http://ri.cmu.edu/
- Colorado School of Mines - http://mining.mines.edu/
- University of Kentucky - http://www.engr.uky.edu/mng/students/undergraduate/
- Massachusetts Institute of Technology - http://robots.mit.edu/
- Pennsylvania State University - http://www.ems.psu.edu/
- University of Queensland (Australia) - http://www.uq.edu.au/
- Stanford University - http://cs.stanford.edu/group/manips/
- Virginia Tech - http://www.vt.edu/
- West Virginia University - http://lcsee.statler.wvu.edu/

Appendix C: Standards

The following standards have some applicability to mining. Note that the only standard specific to mining is "ISO 17757 – Earth-moving machinery and mining — Autonomous and semi-autonomous machine system safety".

International Organization for Standardization (ISO) Industrial Robot Safety Standards

- **ISO 10218-1:2011** - Robots and robotic devices -- Safety requirements for industrial robots -- Part 1: Robots
- **ISO 10218-2:2011** - Robots and robotic devices -- Safety requirements for industrial robots -- Part 2: Robot systems and integration
- **ISO TS 15066:2016** – Collaborative Robot Safety
- **ISO 26262-1:2011** - Road vehicles -- Functional safety -- Intended to be applied to safety-related systems that include one or more electrical and/or electronic (E/E) systems and that are installed in series production passenger cars with a maximum gross vehicle mass up to 3 500 kg. Addresses possible hazards caused by malfunctioning behavior of E/E safety-related systems, including interaction of these systems.
- **ISO 13849-1:2015** - Safety of machinery -- Safety-related parts of control systems -- Provides safety requirements and guidance on the principles for the design and integration of safety-related parts of control systems (SRP/CS), including the design of software.
- **ISO 17757 –** Earth-moving machinery and mining — Autonomous and semi-autonomous machine system safety

In development:

- **ISO TR 20218-1:2017** – Safety of End-Effectors
- **ISO TR 20218-2:2017** – Safety of Manual Load/Unload Stations (MLUS)
- **ISO/AWI 21815** – Earth-moving machinery -- Collision awareness and avoidance

American National Standards Institute (ANSI) Industrial Robot Safety Standards

- **ANSI/RIA R15.06-2012** - American National Standard for Industrial Robots and Robot Systems - Safety Requirements

  U.S. National adoption of ISO 10218-1,2. The purpose of this standard is to provide guidelines for industrial robot manufacture, remanufacture and rebuild; robot system installation; and methods of safeguarding to enhance the safety of personnel associated with the use of industrial robots and robot systems.

- **ANSI/RIA TR R15.306-2016** – Task-Based Risk Assessment Methodology

  TR 306 describes one method of risk assessment that complies with requirements of the 2012 R15.06 Standard

- **ANSI/RIA TR R15.406-2014 –** Safeguarding

  TR 406 explains how to design a system of safeguards to protect human workers in an industrial environment that also contains robot system(s). Supplements the 2012 R15.06 Standard.

- **ANSI/RIA TR R15.506-2014 –** Applicability of ANSI/RIA R15.06-2012 for Existing Industrial Robot Applications

- **ANSI/RIA TR R15.606-2016 –** Collaborative Robot Safety

  U.S. National adoption of ISO TS 15066:2016 – Collaborative Robot Safety.

- **ANSI/ITSDF B56.5-2012** – Safety Standard for Driverless, Automatic Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles

In development:

- **ANSI/RIA R15.08-201X** – Industrial Mobile Robot Safety

- **ANSI/RIA TR R15.706-201X –** Guidance for Users

Canadian Standards Association: CAN/CAS-Z434-03 (R2013) industrial robots and robot systems – General safety requirements

OSHA Robotics Safety Directive

- Title: Guidelines for Robotics Safety
- Directive Number: STD 01-12-002: PUB 8-1.3
- Issue Date: 09/21/1987

Code of Practice – Safe mobile autonomous mining in Western Australia

- Developed by the Government of Western Australia, Department of Mines and Petroleum, Resources Safety 2015
- Designed to provide guidance on mobile autonomous and semiautonomous systems used in surface and underground mines and quarries, and on developing and evaluating safe work procedures for such systems.
- http://www.dmp.wa.gov.au/Documents/Safety/MSH_COP_SafeMobileAutonomousMiningWA.pdf

Appendix D: Facilities available for Research Focus Areas

Safety Research Coal Mine (SRCM) and Experimental Mine (EM) - **Location:** ***NIOSH Pittsburgh, PA.***

The SRCM (Fig. 13) and EM are multi-purpose underground coal mine research facilities. Their four miles of underground workings have been utilized extensively from the pioneer stages of coal mine health and safety research until the present day. The mine layouts are of a room-and-pillar operation. The EM mine entries are approximately the size (about 20 feet in width) of a working section of a coal mine; however, the SRCM entries are only about 12 feet in width thus this could potentially present a limitation for future mine worker health and safety research related to smart mine technologies. Both mines are used for mine health and safety research in areas such as ground control, ventilation, fires, explosives use, materials handling, and environmental monitoring. Currently the electrical power, lighting, and communications systems for both mines are undergoing significant upgrades. The physical dimensions of the SRCM entry width are a major limitation

Figure 13. The Safety Research Coal Mine

Motion Analysis Lab and Human Performance Research Mine - **Location: NIOSH Pittsburgh, PA.**

The Motion Analysis Lab (Fig. 14) and Human Performance Research Mine are both suitable for studying human-machine (or human-robot) interaction. Motion analysis has been used for some time to study these issues, and the potential is similar for collaborative robots and exoskeletons. Early research investigated the influence of machine speed and related factors. Research on safety sensing systems used this technology. In addition to kinematics, electromyography would be a useful tool for looking at muscle loading effects for cases where the machine interacts physically. NIOSH Pittsburgh also has an XSENS suit that measures kinematics without the need for cameras. This system is capable of being used in many environments including our laboratories. In addition to measuring human responses, the motion of machines (or robots) could be measured to assess human performance aspects of directly manipulating a mining machine (or robot), or collaborating with a semi-autonomous machine. The Motion Analysis Laboratory is located on the 2nd floor of Building 152. This laboratory is suitable for studies of human performance on a smaller scale scenario. The Human Performance Research Mine (HPRM) is especially suited to house large machines and would provide a better location for studying human-machine interaction. This laboratory is over 70 feet long by 27 feet wide and has a height of 14 ft. It can be accessed through wide doors on three sides directly from the high-bay of Building 152. It is equipped with motion tracking cameras and also features a fall-arrest system. The size of this space and its motion analysis capabilities make it uniquely well suited for human-machine interaction research. Specifically, the HPRM can accommodate large equipment such as a roof bolter, continuous mining machine, or shuttle car. Human interaction becomes especially important as humans operate machines in a collaborative mode as required when these machines become semi-autonomous. This can change the physical tasks, behaviors, and cognitive demands of people in new and unforeseen ways. In summary, the Motion Analysis Lab and the Human Performance Research Mine have capabilities to measure a wide range of kinematics to answer associated research questions.

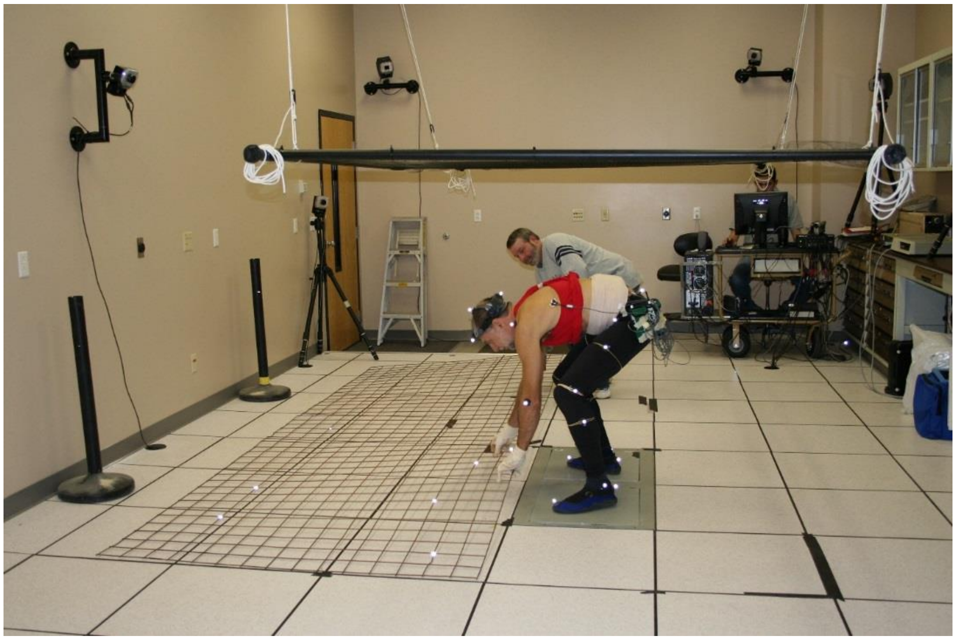

Figure 14: Motion Analysis Lab

***VISIlab* - Location: NIOSH Pittsburgh, PA.**

The VISIlab facility (Fig. 15) was constructed to conduct research on the use of immersive virtual environments to improve mine safety and health. The facility includes a unique state-of-the-art 360° cylindrical projection system that uses stereoscopic 3D technology to enhance the immersion and experience of the users. It has the capability of putting an entire group into a virtual environment that they can interact with, providing an intuitive and immersive training experience. An adjacent 50° curved display acts as a classroom environment for instructor-driven sessions and as a post-simulation debriefing environment following the sessions run in the 360° environment. Additionally, the lab has eye tracking hardware and software integrated with images displayed on the projection system. This enables the study of situational awareness, hazard detection, interactions with autonomous and semi-autonomous mining equipment, and the visual attention locations when using operator displays to monitor or remotely control mining equipment. Overall, the lab is well suited to support the studies of human-machine interaction and the study human behavior and perceptions when encountering autonomous or semi-autonomous mobile mining machines in a virtual mine setting.

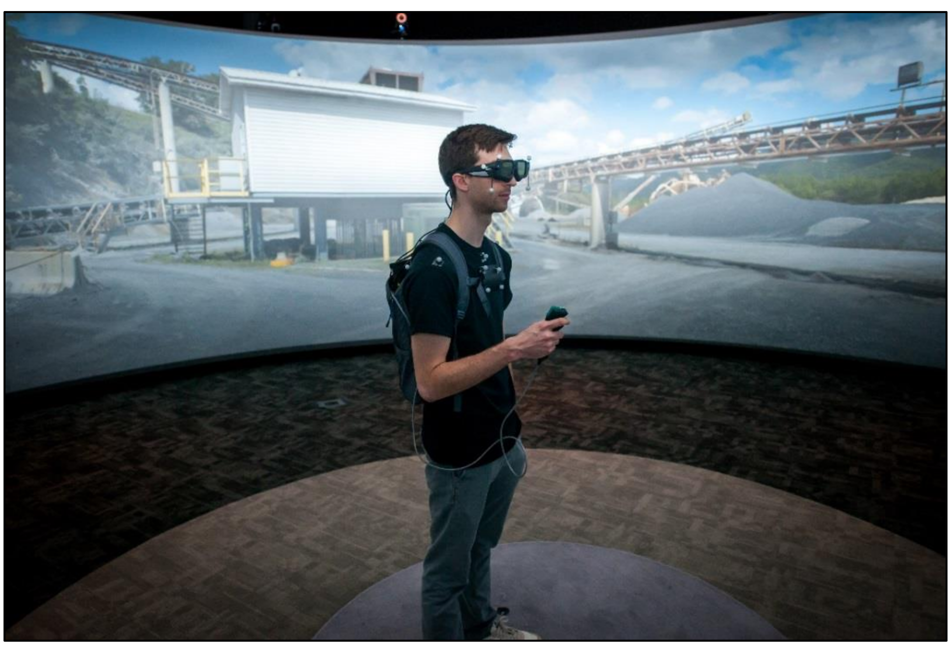

Figure 15. Eye tracking of panoramic mine scenes in the VISIlab laboratory.

***Radio Frequency Shielded Laboratory* - Location: NIOSH Pittsburgh, PA**

Built in 2010, NIOSH's radio frequency (RF) shielded lab (Fig. 16) was designed as a critical component to evaluate communications system components in support of the MINER Act requirements. It was used to isolate noise sources to characterize antenna distribution patterns. The RF lab provides about 240 sq. ft. of shielded space separated into two sections inside to house laboratory grade measurement equipment. The lab provides almost complete suppression for most conventional radio frequencies used in mining.

Figure 16. Exterior and cutaway of interior of radio frequency (RF) shielded lab.