Advanced Measurement Methods in Mining

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Dean H. Ambrose

43.1 Introduction

Mining and processing earth's materials form the basic building blocks from which many technological advancements and products are made. Virtually all metallic and non-metallic products are derived from a substance found in our earth that we blend, mold, extrude, or pulverize into something useful. The mining industry is responsible for the first step of this process: extraction from the ground. Mining, particularly coal mining, poses significant risks to both humans and machines. As raw materials are forcibly broken or blasted apart, then roughly yet effectively excavated by large transport vehicles or by vertical and incline hoists, human operators must battle noise, dust, mud, and darkness while controlling and maintaining their machinery and keeping themselves and their crews safe from harm. Such a hazardous work environment poses extraordinary challenges to mine operators who must vigilantly recognize and control the perils of mining.

While mining is essential to the progress and productivity of our society, the early years of mining was characterized by miners' poor health, common accidents, and environmental impacts. Poor safety and health practices were costly in both personal injuries and property damage. Thanks to safety and environmental regulations and diligence from the mining community, mining safety records have significantly improved over the last 50 years, and progress in this area continues.

As digital human modeling (DHM) been more prevalently used by human factors and ergonomics professionals to analyze workplace hazards and improve workplace design (Brown, 1999; Badler et al., 2002; Chaffin, 2002; Määttä, 2003; Ferguson & Marras, 2004; Colombo & Cugini, 2005; Zhang & Chaffin, 2006), the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory (PRL) also saw the benefits to using DHM in their computer-simulated mining environments. This chapter features how researchers use DHM to assess and ultimately decrease the occupational risks and threats faced by underground coal mine machine operators.

43.2 Understanding the Mine Environment

The mining environment can be likened to a hostile workplace. Miners work with excessive noise levels in poorly illuminated areas, and may be exposed to toxic gases and dusts, excessive heat, humidity, and vibration. The machines are powerful, dangerous, and mobile with swinging, moving appendages and spinning, jagged, grinding cylinders (fig. 43.1). Miners confront roof falls or other wayward debris from the face or walls of the mine, inherent dangers of operating electrical equipment, malfunctioning machines, ignition and explosion hazards from gases and dust, mine fires, and sudden inundations of water or gas.

Mining is inherently uncomfortable. Prolonged stress from the mining environment often exceeds human tolerance levels. Stress factors often overlap and contribute to decreased alertness or performance and reduced productivity. Noise levels coupled with redundant machine tasks, for example, could induce fatigue or complacency and increase the chance of an injury or fatality.

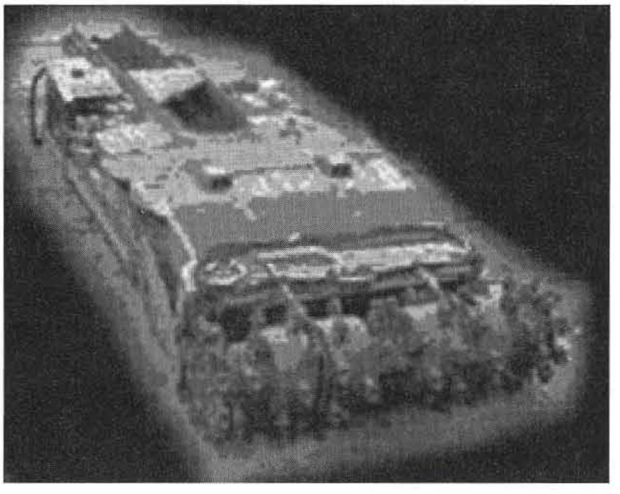

FIGURE 43.1 Cutting cylinders on a continuous miner machine. (Photograph courtesy of Joy Mfg., Franklin, PA.)

Ongoing efforts strive for miners' protection, resulting in healthier miners and safer mines. The approaches taken by the mining industry have validity in any industry concerned with the health and safety of its workers. These are: engineering control, machine safety, industrial engineering, training, regulations, and unions.

Engineering control helps reduce exposure to potential hazards either by isolating the hazard or by removing it from the work environment. Here it includes mine design and equipment and workforce selection. *Machine safety* is a prominent concern inherent to the hazards of working in a mechanized environment, and includes automation and remote control technology. *Industrial engineering* refers to human factors and ergonomics, applying information from human characteristics, abilities, expectations, and common behaviors to the design of machines, procedures, and even the environments in which the miners operate. Adequate *training*, from initial job orientations to refresher training for mining veterans, must take into account new technological changes as the industry advances. Federal, state, and local *regulations* play an important role in controlling mine hazards, developing mandated training for the entire mining industry and a certification system for instructors. Mine *unions* have taken a major role to ensure that miners' safety and health remain as important as, if not more than, the daily production in mines.

43.3 "Measuring" in the Mine Environment

Accident statistics provided by the Mine Safety and Health Administration (MSHA) are extremely helpful in establishing trends of injuries and fatalities relating to specific mining machinery, job titles, accident and mine type, and so on. However, Smith (2006) finds that accident reports from MSHA are primarily focused on violations of mine laws, and lack helpful detail for researchers who are attempting to discern the root cause of injuries and fatalities. Furthermore, Ambrose (2003) states that MSHA accident investigation report narratives contain minimal information to facilitate studying interactions between machines and their operators.

Traditional mine research data are collected via field testing at an actual mine, or in a laboratory. It takes particular commitment for an active mine to work a research team's field tests into their production schedule. The research team must be qualified to operate within an active mining environment, and undergo mandatory mine training. They must also have personal safety and protection gear. In addition to the hazards and dangers identified earlier, the research team is still faced with variable and uncontrolled test conditions. They may have limited access to mine locations and personnel. Also, they may have no control over where or which machines or instruments are being used during their "time slot" for testing. In a laboratory test, researchers develop scaled or full-scale mockups of mine environments, equipment, and machinery. Laboratory tests (fig. 43.2) are useful for creating optimum test

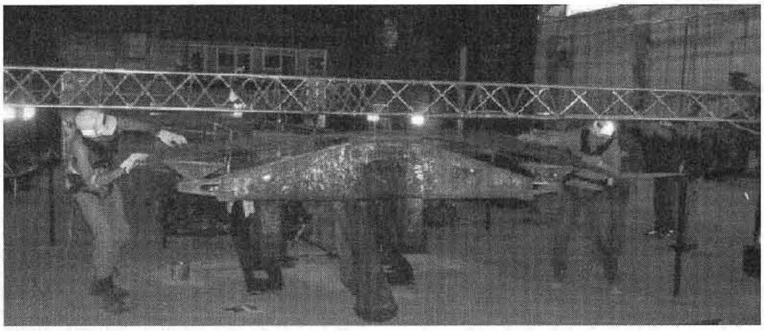

FIGURE 43.2 Test subjects remove wire mesh from actual equipment under replicated mine seam height conditions.

conditions without time constraints; though they lack much of the realism of actual mine conditions, and experienced mining operators may not always be available for the tests. Both methods incur significant time and expense.

When DHM was first identified as a possible method of conducting mine research in the mid-1990s, an initial literature review by PRL found no previous DHM applications in the mining industry. An expanded search into the automobile, agricultural, factory floor, and sports industries provided much information. Early research endeavors (Ambrose, 1996, 1999, 2000a and b) reflect the learning curve in what is now a 10-year span of research incorporating DHM in safety and health for mining.

Aside from the problems associated with field tests in actual mines and laboratory tests, it should be noted that DHM has its own limitations. Researchers must be concerned with their organization's or industry's acceptance of DHM predictions, and the databases from which outcomes are derived. Decision makers within any industry must be able to justify their investments in new technology, and the consequences of such investments in terms of potential research results and their approval by stakeholders and customers. Embracing DHM also means researchers must be able to effectively communicate the results of their work for proactive uses, and show some measure of their research effectiveness. DHM is in competition, so to speak, with more tangible research results such as redesigned equipment, patents, or a quick turnaround response to a specific injurious or fatal incident. Nevertheless, DHM is becoming a recognized and proven research tool with potential to design products and systems, to study and apply human factors and ergonomic principles, and to serve as an effective vehicle for advocating safety and health research, as evidenced below.

43.4 Capturing Human Motion

PRL uses motion-capture technology in their simulation research methods. Motion capture technology (fig. 43.3) is a technique that uses the human body, or other object, as an input device. In most applications, sensors or optical markers are placed on the subject's body and the motion capture system monitors and records the subject's motions. If done properly, motion capture provides high-quality data more quickly and efficiently than traditional frame-by-frame animation techniques. Because the technology captures movement data directly from an actual subject, the data are much more accurate.

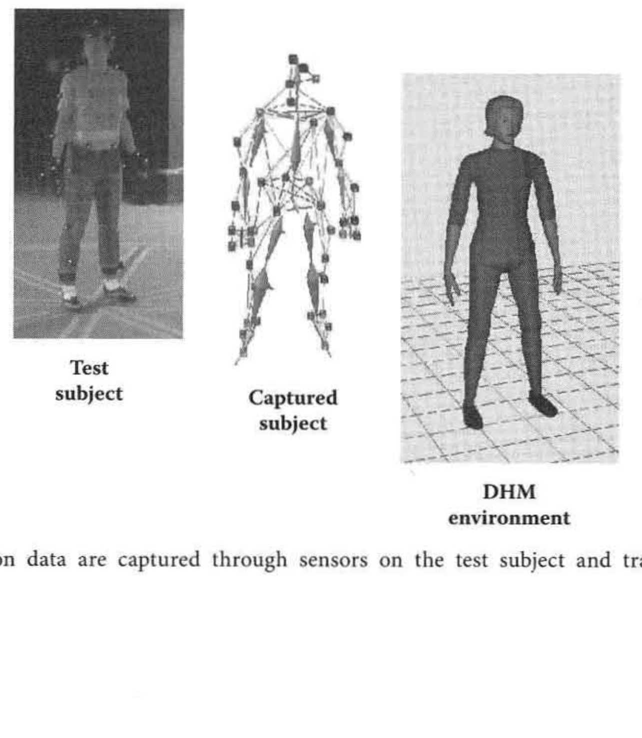

FIGURE 43.3 Motion data are captured through sensors on the test subject and transferred to a DHM environment.

Motion, particularly human motion, is very subjective. There are subtleties in human motion that a motion tracking system will detect, but a human eye will not, using traditional key frame animation techniques. Motion capture systems provide an accurate, convenient, and quantitative assessment of functions by providing comparative or absolute motion measurements.

Specialized DHM simulation and analysis software sometimes is packaged with a motion capturing software module, providing an interface to a motion capture system. The result is a rather compelling research tool. Each sensor or reflective marker on a subject transfers data through a motion capture system into a DHM software environment. Both the position and orientation of each sensor are tracked and mapped to a virtual human with a predefined figure, enabling the virtual human to mimic the motions of the test subject, which can be saved for future analysis. If the connection between the motion capture system and the DHM software supports it, computer-generated objects, such as a virtual human, move in real time with the real-life subject. Therefore, investigators can observe real-time results on the virtual display, providing instant information that can significantly augment the experiment. Such DHM simulation has been used at PRL to conduct a detailed examination of lower back movement and muscle stress, virtual human joint information, muscle stress from hand loading mining material, and body part strength. This chapter explores these investigations in further detail in later sections.

PRL uses two primary types of whole-body motion capture systems, *electromagnetic* and *optical*. Both types are quickly becoming standards in the movie production, automobile, and military R&D communities for creating and studying animated motions of characters (and on the Hollywood side, for creating special effects). There are pros and cons to both types.

PRL's electromagnetic motion capture systems use tether sensors attached to the test subject, which then move within an electromagnetic field created by a transmitter. These sensors pick up changes in the electromagnetic field and the corresponding positions are fed to a controller connected to a computer workstation that processes the motions in real time. The electromagnetic system has no possibility of blocked or occluded markers, thereby allowing real-time motion processing and instantaneous playback of captured data.

Setting up an electromagnetic motion capture system isn't very complicated, but it is particularly sensitive to metal, including steel support columns or beams, steel-reinforced concrete floors, overhead light housings, metallic studs in walls, filing cabinets, and so on. In addition, electromagnetic systems work best in smaller performance areas using slower data rates, which limits capturing fast motions and motions in a broad space. Cable harnesses inherent with PRL's electromagnetic systems can pose a problem for more athletic test motions, and can unintentionally snag on stationary objects within the test field. Compared to an optical system, electromagnetic systems typically require less setup time and are more cost effective.

PRL's optical motion capture system uses reflective markers attached to a test subject, who is then digitally filmed with special high-resolution infrared cameras and an infrared light source. The digitized information feeds into a computer workstation that controls the optical tracking system and records the motions. The markers provide two-dimensional points for each camera, which the motion capture software translates to three-dimensional coordinates. Significant processing power is required to resolve two-dimensional camera data to three-dimensional motions data, possibly causing instant playback to be riddled with occluded markers. If test subjects get too close or markers overlap, it could confound the software. To combat these issues, a newer feature of motion capture software technology is biomechanical intelligence, which "knows" the human body and can compensate automatically when occlusion occurs. This allows real-time motion processing of captured data and instantaneous playback through DHM software.

Unlike their electromagnetic counterpart, optical systems allow unencumbered motion for a large number of markers in a fairly large space, and are unaffected by metals. For example, it's possible to track multiple subjects, each with 50 sensors attached, in a 900 square foot area, noting that area and accuracy are directly related to the number of, and positioning of, cameras and infrared light sources. Of course, setup time is typically more time consuming for optical systems, allowing for camera

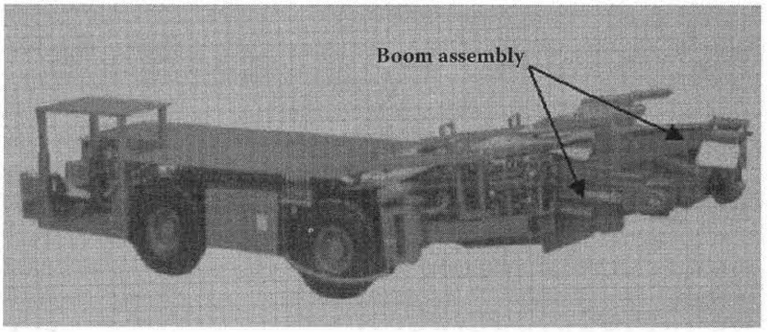

FIGURE 43.4 Actual dual boom arm roof-bolting machine (Photograph courtesy of J. H. Fletcher & Co., Huntington, WV.)

positioning, calibrating all equipment, and masking unwanted infrared sources in the test area. Once setup is complete, the high-speed, high-resolution infrared cameras used in optical systems can accommodate high data rates such as 2,000 frames/second, allowing for extremely accurate capture of even high-speed motion. This has particular relevance to obtaining accurate samples of sudden motions, such as equipment operators avoiding moving machines or machine appendages. Motion capture is an effective validation and verification tool for digital human models. Woolley et al. (1999) suggest that human motion studies using dynamic biomechanical analyses or human motion simulation models should establish an empirical motion database. Efforts are underway. An Ambrose et al. (2005a) study used motions from movements of roof bolter appendages (fig. 43.4) and 12 human subjects with mine machinery experience to verify that the model's simulation predictions represent an accurate picture of the machine model and operator during roof bolting tasks. Valid random motions reported by Ambrose (2000b, 2001), and Volberg and Ambrose (2002) used the same 12 human subjects to study aspects of operator movements, the range of motion of operators, and variation in those movements. The same valid database of captured human motions contributed to the Ambrose et al. (2004) investigation of low back stress experienced by machine operators. The captured anthropometry of each of the 12 test subjects validated the database used by Ambrose and Cole (2005) to evaluate control interventions that reduced the severity of muscle recruitment and spine loads resulting from roof bolting in different work postures and seam heights.

New human subject testing (Bartels et al., 2008) used 10 additional subjects to supply movements from experienced miners to help validate motions representing the sudden movements necessary to avoid

FIGURE 43.5 Test subject operating a roof-bolter boom arm assembly mockup.

moving mine machinery that can influence the industry standard for a specific machine's ground speed. This growing database will be integrated with DHM motion capture data and machine models to accurately simulate the operator working around a specific machine, and predict probable impact incidents through collision detection. Another new human subject test (Kwitowski & DuCarme, 2007) furnished movements from 12 experienced miners that will help validate motions that correctly mimic a machine operator controlling the horizontal motion of an appendage from a roof bolter machine (fig. 43.5). Further use of this database with DHM will examine low back stress experienced by these machine operators during this task.

43.5 DHM Technology Applications in Mining

This chapter has already established the unique and severe environmental conditions in which miners perform. Environmental stress and restrictions, particularly the restricted vertical workspace in many underground coal mines, make mining one of the most difficult industrial environments in which to make safety and health improvements. Studying the interaction between people and their environment, regardless of the industry, is essential to determining causal factors behind fatalities and injuries, and in developing controls to help prevent them. This section suggests methods for using DHM to understand and solve human-machine interactions.

Investigators must be discerning with DHM data. They must refrain from generating more data than needed, or read more from the database than what the model and simulations were designed to deliver. The model is only as good as the system it defines; certain parameters must be validated using real subjects and undergo further enhancements to streamline its efficiency. One must remember that DHM results are only predictions of outputs from events or conditions that *reflect* the real world through a virtual world. With real-world logistics—such as travel to mining sites and costs associated with experiments—no longer a factor, it's very easy to become overwhelmed with data because it's now possible to generate and track so *much* of it. Good research and intelligent conclusions that will benefit industry are served by planning simulations well, and judiciously using the right data for the right job.

43.6 Using DHM to Depict Motion and Behavior Variation

Early DHM software effectively portrayed simple movement behaviors and basic motions, but failed to capture the random nature of human motions or to depict path variance within human motions. The key to delivering motion variability in DHM involved the concept of *stochastic modeling*, but how was this to be accomplished in the DHM world? Ambrose (2001) reported a simple technique for representing and analyzing motion variations and hazardous events in a computer-simulated three-dimensional workplace using DHM software. Later, Ambrose (2004) discussed this same technique and detailed the code development for a model that demonstrated random human motion and behaviors. Now it was possible for researchers to study hazardous interactions in a virtual environment, in this case, unintentional contact between mining operators and mining machines.

In an underground coal mine, miners are at risk from being struck by the mining machinery due to the confined workspace. Miners who worked around roof-bolter machines were particularly susceptible to unintentional contact incidents, and researchers used DHM to increase miners' safety while working around this machine. In order to effectively study unintentional human-machine contact, the simulation had to account for random motion and behavior of the operator.

Basic motions and standard deviation data provided random parameters for the operator's movements in the random motion code. Each of the basic motions provided sets of three-dimensional (xyz) values. Results from motion envelope analyses by Bartels et al. (2001) provided standard deviation values. Applying standard deviation values to basic motions helped researchers devise "manipulation values" that used xyz-orientation angles and xyz-positional coordinates to define a set of final postures of

TABLE 43.1 Random Hand Motion Rules for a Roof Bolter Machine

Motion direction		Operator's Hand Motion Type						
		Basic	Prominent vertical direction	Vertical with z direction	Vertical with x direction	Point to point	Leaning forward and backward	Starting position
orientation angles		x	x	x	x	x	x	x
		y	y	y	y	y	(random y)	y
		z	z	z	z	z	z	(random z)
positional coordinates		x	x	x	(random x)	(random x)	x	(random x)
		y	(random y)	(random y)	(random y)	(random y)	y	y
		z	z	(random z)	z	(random z)	z	(random z)

the virtual human. Using positional x as an example, x is equal to multiplying the original x value from the basic motions by the standard deviation value from experiments on motion envelopes than minus a random number from zero to twice the standard deviation value for x. Tables imbedded into the code defined the standard deviation values, also called seed variables.

Guidelines were established (Table 43.1) that used manipulation values to cause random motion, which made it possible for investigators to program code correctly to recognize the motion's direction and how random changes affect basic motions. These guidelines also maintained directional integrity of the virtual human's intended or expected basic motions while providing random elements within those motions.

In contrast to random motions, random *behaviors* were easier to define. A random behavior is simply a series of human motions that mimic a specific action. Investigators can use statistical information about a job function to identify risky worker behavior with a model through a decision algorithm that formulates and determines what behavior to use during the simulation.

Results from this random motion and behavior study using DHM can provide increased awareness to workers and even potentially impact the engineering and design of the machinery. Finding the right software tool with all the features and capabilities to develop and execute customized computer code for virtual motions and behaviors was critical to this effort.

43.7 Using DHM to Determine Subject Response and Reach Envelopes

Due to a restricted workspace, miners are often forced into uncomfortable postures and encounter limited reach capabilities. DHM software has effectively depicted simple response and reaching movements. But the operator postures unique to operating machines in underground coal mines prompted the Bartels et al. (2001) study to measure human motion response times and motion envelopes in a restricted environment. Human motions were captured and recorded using a motion tracking system, as described earlier in this chapter. The following lessons learned from the Bartels et al. (2001) study have applications in any DHM model and simulation human response and motion envelope study.

43.7.1 Test Normal Subject Movements

To prepare for the motion capture, researchers set up a mock mining environment that included a wooden replica of a roof-bolter boom arm assembly (fig. 43.6). Test subjects were asked to position themselves around the roof bolter as they normally would for different job tasks, providing unique starting point data for each operator. These data were useful in analyzing collisions that occur between operators and an appendage from the roof bolter, and in examining a variety of reach envelopes from the test subjects in different work postures.

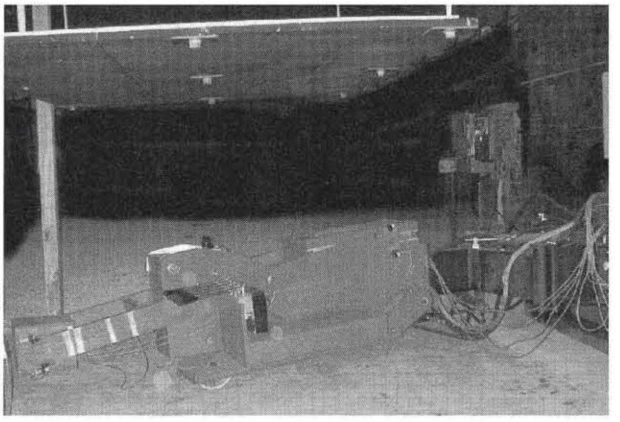

FIGURE 43.6 Mock mining environment includes a wooden replica of a roof-bolter boom arm assembly and adjustable roof to vary the seam height.

43.7.2 Exercise Repetition of Test Trials

Subjects repeated the test trials three times for each independent variable combination under investigation. In this study, variables included differing coal seam heights and work postures such as subjects kneeling on one or both knees, squatting versus stooping, and standing. Repeating the trials made a much more useful statistical analysis of the motions being captured. To help minimize fatigue, subjects were allowed to rest at least two minutes between repetitions.

43.7.3 Capture Quality Data from Test Subjects

Test subjects were instructed to follow standard, specific procedures relating to their job, operating a roof-bolter machine. If test subjects have difficulties following procedures, it's practical to dismiss those subjects or simply keep trying repetitions until they reach the desired number of successful trials, otherwise the data are not valid for the study's assumptions.

43.7.4 Structure Response Times

To capture accurate response times for all subjects, it's wise to create a common starting pose for all response time testing. Researchers staged each test subject relative to a specific point on the subject's body and to another specific point on the machine. Subjects were instructed to complete a roof-bolting task sequence, but when they received a verbal cue, they were to move as if to avoid being struck by a roof-bolter appendage. The timing of the verbal cue was random so the subject wouldn't be able to anticipate the action.

43.8 Virtual Human Vision

Virtual human vision is often overlooked when studying worker safety and health, perhaps because the ability to clearly see people, other machines, moving machine appendages, work area's characteristics, and environmental hazards seems obvious. Yet the inability to see people, objects, and hazards has contributed substantially to mining incidents and fatalities, and must be accurately accounted for by simulations. DHM software accounts for virtual human visual capabilities using a vision cone, which defines an area extending from the virtual human's eyes, or using a separate window that shows what the virtual human can see (fig. 43.7). Advancements in DHM software now allow vision tracking and

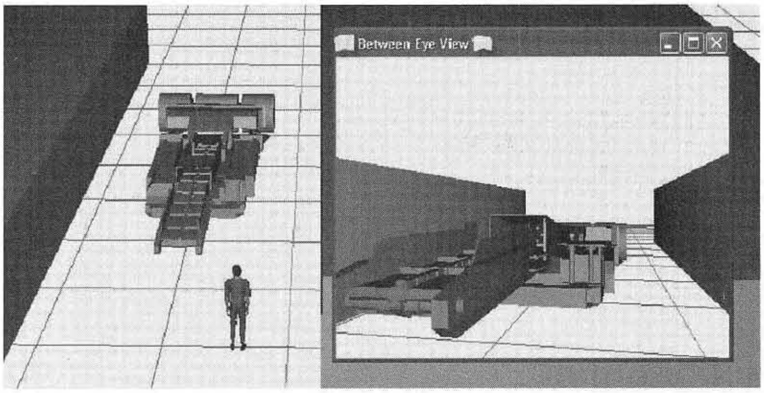

FIGURE 43.7 DHM mine environment with eye view of the machine operator inserted.

recording of objects seen, and not seen, by the virtual human. The following discussion describes how virtual vision was used to advance safety and health concerns using models and simulations in DHM software.

43.8.1 Vision Cone

When examining a database of collisions between a miner and mining machine appendages, the investigator needs to ensure the data accurately reflect the real world. Early investigation by Bartels et al. (2001) used a viewing area defined by an oval directrix model characterized by Humantech (1996). This viewing area looked like a cone extending from between the virtual human's eyes. Bartels et al. (2001, 2003) modified the cone to determine the optimal viewing area for unique lighting conditions found in underground mining environments. Surprisingly, a subject's vision cone was significantly reduced by the bill of a standard hard hat. Figure 43.8 shows the angular data of the viewing area for normal light, modified light (0.06 fL with cap lamp), and simulation (original area of the virtual operator). This study set the standard for virtual human vision within an underground mining environment while operating roof-bolter equipment.

43.8.2 Viewing Area

Investigators were also concerned with a virtual human's view, when considering operator response time to the event when the operator sees a moving object and gets out of the way of it. Using the modified viewing area already discussed, eight reference points on the viewing cone were identified (fig. 43.9). During a simulation, researchers recorded and calculated the distance between these reference points and a reference point on another object, such as a boom arm of a roof bolter. Bartels et al.'s (2001, 2003) experiments validated the premise that when one or more of the eight resulting distances was negative, the virtual operator couldn't see the boom arm. From this study, the DHM industry was better able to address vision tracking and recording of objects as seen by virtual humans.

43.8.3 Line of Sight

The mining industry was challenged to define an adequate field of vision for operators seated in cabs of earth-moving equipment, whose unique specifications simply were beyond conventional line of sight and conical section analysis techniques (Hella et al., 1991, 1996). Eger et al. (2004, 2005) used obscuration zone and coverage plane features in DHM as an effective tool for evaluating line of sight in earthmovers, yielding important enhancements to underground mining machine design. The technique can

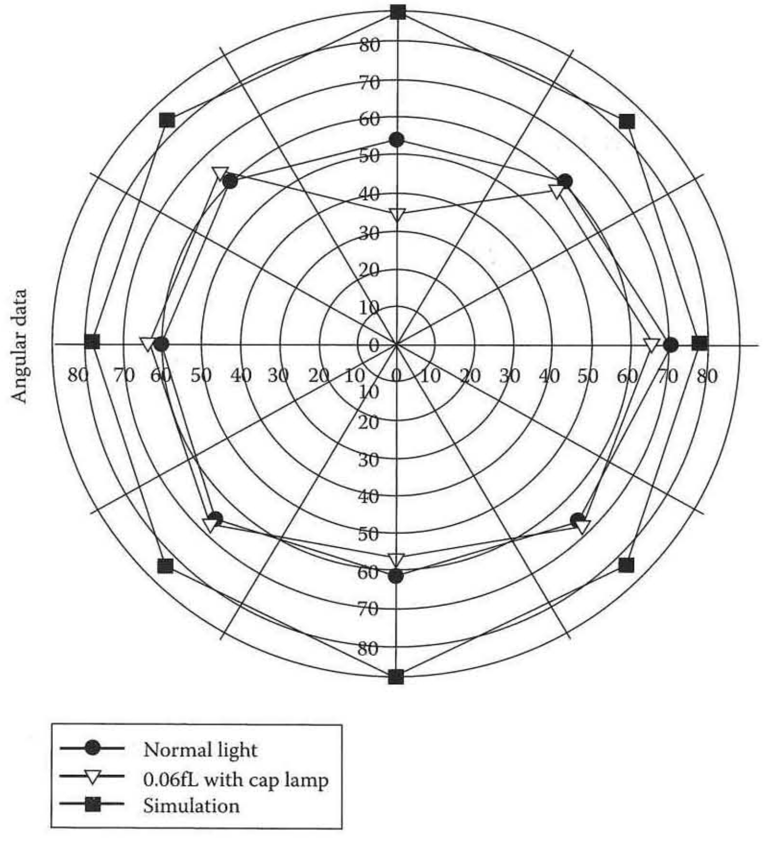

FIGURE 43.8 Angular data of the viewing area for normal light, cap lamp. and simulation.

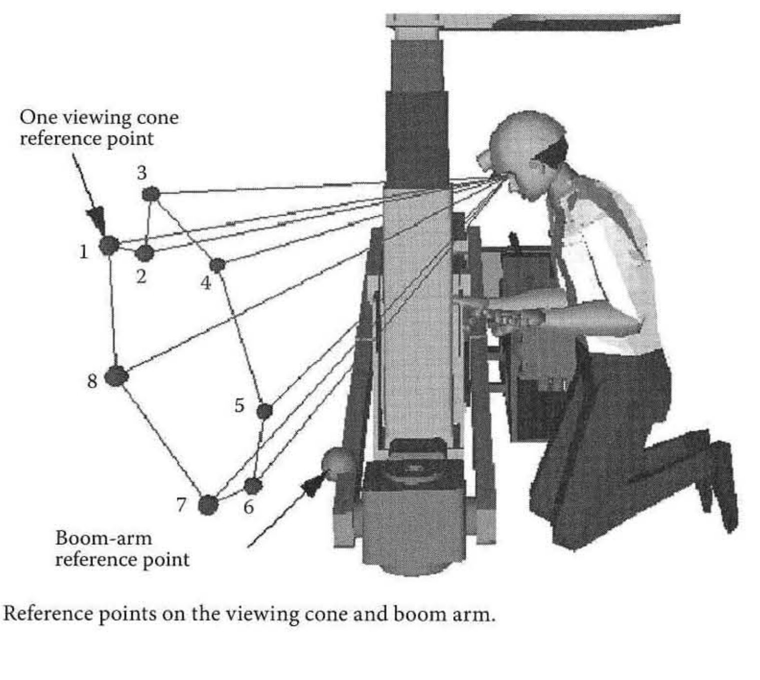

FIGURE 43.9 Reference points on the viewing cone and boom arm.

by used on any machine component, and involves using obscuration zones to show regions of space not visible to the operator. Coverage zones were generated with colored grids indicating visible and non-visible zones. Subsequent equipment enhancements provided greater visibility to operators within the cab of earth-moving machines.

43.8.4 Value Attention Locations

A very important visual aspect of mining machine operators is called value attention locations (VAL), key visual areas in which miners control and operate their machines. The mining industry also uses an educational aid called "red zones are no zones" to help remote-controlled machine operators understand which areas around their machines they should avoid, and to reduce the injury and fatality rates from miners making contact with moving machines. Bartels et al. (2007) used DHM vision tools and survey data to define the VAL for operator positions, the logic behind choosing various positions, and to define the operator's direct focus area during various tasks. The results to date provided preliminary recommendations for control interventions that enhance VAL, decreasing safety and health risks to mining equipment operators. In addition, researchers plan to use DHM illustrations to assist adopting new mining techniques and procedures, as well as applying technological advances to equipment to enhance VAL.

43.9 Using DHM to Characterize Machine Designs and Controls of Mining Equipment

As recently as the mid-1950s, one third of all coal produced in the United States was hand loaded. Physical demands on mine workers have been greatly reduced primarily due to advances in mechanization during the second half of the 20th century. The past decade has seen new mining technologies such as remote control, continuous haulage systems, and automated equipment. However, the physical demands on miners remain significant. Human-centered design principles have been minimal as new equipment and new technologies in the mining industry have surfaced, as recognized by Ambrose (2000a and b, 2003), Ambrose et al. (2005b), Cornelius and Turin (2001a and b), Cornelius et al. (2001c), and Steiner et al. (1998).

Operating equipment at the mine face, the point of coal extraction, is one of the most fundamental and risky elements of underground mining. It is performed in restricted workspaces with reduced visibility. Studying safety and health issues surrounding face equipment is extremely complex. Face equipment, such as roof bolters and continuous mining machines, are not only dangerous when performing tasks at the face, but also when moving from one task site to the next. These machines pose significant dangers to both the machine operators and their helpers, putting humans in awkward postures for tasks and requiring fast reactions to avoid being struck or pinched by moving equipment and machine appendages. Since it's neither feasible nor ethical to use human subjects to directly evaluate factors that precipitate such injuries in the field or in laboratory experiments, these machine design and control practice concerns are being addressed by researchers with the help of DHM.

43.9.1 Machine Appendage Speeds

Roof-bolter operators in underground coal mines have a high incidence rate of being struck by the roof bolter's drilling boom (fig. 43.10), often resulting in serious injury or fatality (MSHA, 1994). Ambrose (2003), and Ambrose et al. (2005a and b) used motion analysis data and DHM to analyze accident risks of miners working with roof bolters, manipulating key factors that influenced injuries including the speed of the roof-bolter boom, boom direction, vertical space constraints and work postures, operator location, operator sizes, and hand positioning behaviors when operating the roof bolter. The most

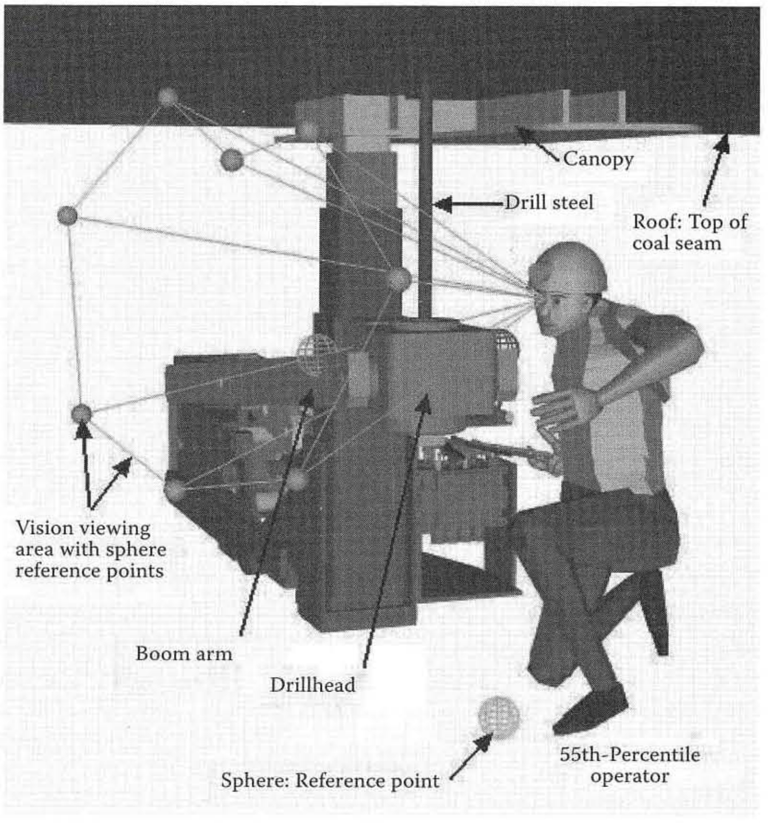

FIGURE 43.10 A view of a DHM mine environment with a roof-bolter model and virtual operator.

influential variable in causing a struck-by incident was boom speed. Operators working in a more restricted vertical workspace, in which an upright position was not possible, experienced greater struck-by risks than operators able to maintain an upright posture. Likewise, larger operators were at greater risk compared to average sized operators. This investigation identified the safest boom speed parameters for varying vertical workspaces and operator sizes.

43.9.2 Machine Tramming Speeds

In previous studies, Ambrose (2001, 2003) simulated an operator's behavior and machine motion to accurately predict and identify hazards, and used that information to form safe design parameters for mining equipment. Bartels et al. (2008) combined motion capture data and DHM simulations to gather struck-by and pinched-by data using collision detection features of DHM. This will determine safer workplace positions and safe tramming speeds for a continuous mining machine (fig. 43.11), one of the most basic and dangerous pieces of underground mining equipment. DHM simulations let researchers study multiple environments and virtual humans in differing scenarios that would be hazardous and cost prohibitive in field studies.

43.9.3 Mechanical versus Electronic Joystick Controls

In low-roof (also called low seam height) mining conditions, miners experience injuries from repetitive motions to their wrists, elbows, and shoulders while in different work postures such as kneeling

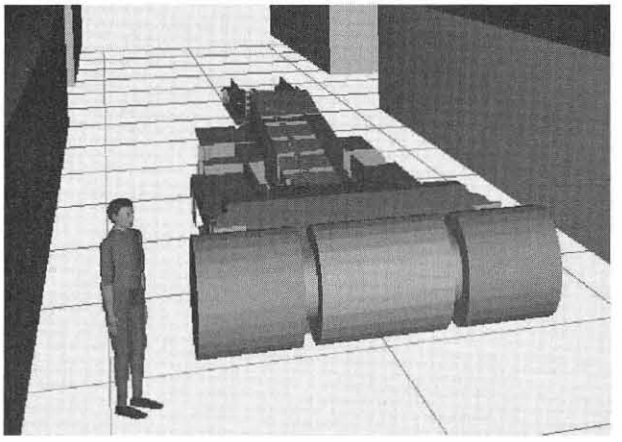

FIGURE 43.11 A DHM mine environment with continuous miner model and virtual operator.

on one or both knees. Exposure to these and similar stressors is a recipe for musculoskeletal disorders. Using DHM simulations, Ambrose et al. (2007) predicted joint moment and joint force effects to the right wrists, elbows, and shoulders of roof bolter operators while using electronic and mechanical joystick controls. As expected, electronic joystick controls significantly reduced joint movement and force compared to mechanical joystick controls. Using DHM in this study facilitated the estimation of upper extremity loads on equipment operators. Despite its findings, DHM data must still be validated in real-world situations through an epidemiological assessment of equipment operators in the field. For example, despite the physiological benefits of an electronically controlled joystick, it doesn't provide as much physical feedback as a mechanically controlled joystick. Some operators may prefer, or even need, the "feel" of the mechanical joystick feedback to safely and efficiently handle the machine.

43.9.4 Mining System Designs and Procedures

In Poland's mining industry, most mining accidents occur in anthracite coal mines, with the majority of fatalities occurring in underground coal mines around mining machines and equipment. Similarly in the U.S. mining industry, the majority of accidents occur in underground bituminous coal mines, with the balance occurring in surface mines. Dudek et al. (2005) used DHM simulations to help identify technical risks in standard Polish mining systems (longwall and roadheading) and devised methods to reduce or eliminate those risks. DHM simulations with mining machines were performed even before mining machine prototypes were manufactured, giving manufacturers the opportunity to make changes early in the design process, a significant economic advantage. By taking human factors into account, researchers and manufacturers developed a realistic picture of both operational conditions and human behavior. Potential machine operator mistakes were identified early enough to impact machine design and/or mining system procedures.

43.10 Ergonomics Analysis: Using DHM to Illustrate Material Handling in the Mine Environment

As previously illustrated, miners encounter physical demands and environmental restrictions that include confined workspaces, necessitating awkward postures, working in muddy or wet floor conditions, exposure to high levels of whole-body vibration, and performing significant heavy manual work. Back injuries from handling materials in underground mines continue to pose a major safety concern. Despite numerous mechanized aids, Patton et al. (2001) found that the number of materials-handling injuries remains the second most common injury in underground coal mines. Earlier studies by Gallagher et al. (1997a and b) developed recommendations for manual lifting tasks in underground mining, and examined the effects of posture on miner's back strength while kneeling and standing. The following DHM applications illustrate this enabling technology as an exceptional research tool that profoundly changed ergonomics analyses methods for studying low back issues in mine workers.

43.10.1 Lifting and Walking Stress Analysis

One of the major contributors to lower back disorders in any environment is simply lifting things. Proper body posture and keeping objects at the proper proximity to the body help reduce lower back strain when lifting or handling objects. PRL used DHM animations to train mine workers on proper lifting and carrying postures. The DHM carried an average load for a miner, represented by 40 pound wire-mesh, in a variety of typical underground mining scenarios. The objective was to make mine workers aware of proper body posture when lifting, and to instruct mine workers to keep loads close to their bodies when lifting or handling loads. A DHM's *watchdog* feature of the low back analysis was applied and changed colors to show when forces on the lower back increased (red) or decreased (yellow or green).

43.10.2 Spinal Load Analysis for Machine Operators

Ambrose et al. (2004) effectively used DHMs to evaluate the severity of muscle recruitment and spinal loads while operating a roof bolter in different work postures and mine seam heights. Researchers generated a database containing L4/L5 spinal joint and back muscles by processing captured motions from test subjects using DHM. They then analyzed the variance of the forward bending moment, for both standing and kneeling postures, using maximum values for spinal forces and moments, and estimated muscle forces from 10 trunk muscles. The results showed that an operator's forward bending moment increases significantly from a standing posture, while the compression force and trunk muscle activity were greater from the kneeling posture (fig. 43.12). DHMs in kneeling postures demonstrated an increased forward bending moment, twisting moment, compression force, and trunk muscle activity for lateral movements and extended torso in a 45-inch seam height versus a 60-inch seam height.

This research led the way for Ambrose and Cole (2005) to evaluate control interventions with DHMs that reduced the severity of muscle recruitment and spine loads for roof-bolter operators in different postures and seam heights. This study illustrates the benefits of using DHM to estimate spinal loads for equipment operators using what-if scenarios that contrast human motion in the workplace with control

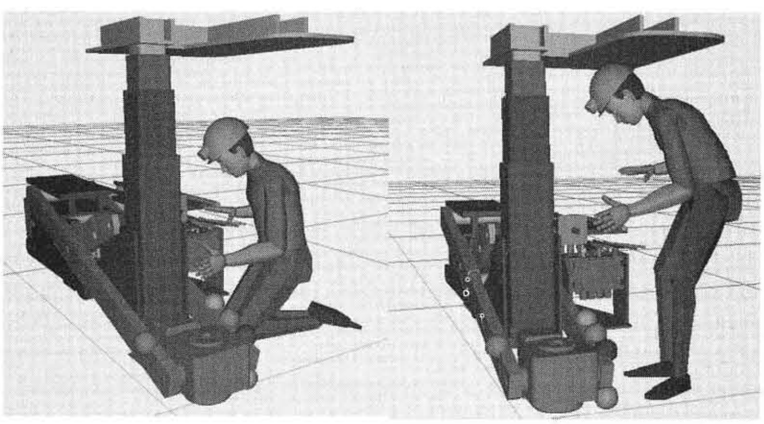

FIGURE 43.12 Illustration of forward bending comparing a standing work posture and a kneeling work posture.

interventions. The first database contained L4/L5 spinal joint and back muscles generated by processing captured motions from test subjects using DHM. A second database repeated this generation with job materials (drill bit, bolt, and wrench) that were one-half the normal weight. Finally, a third database repeated the generation once again using the bolting process that mimicked the subject performing tasks with full-weighted materials relocated to different positions. Comparing the resulting databases indicated that all work postures and seam heights benefited from a reduction in the weight of materials handled, and showed a significant decreased response force when the materials were relocated.

43.10.3 Reconstructing Material Handling Accidents

Winkler et al. (2005) first used DHM to visualize accidents involving handling materials in the mining industry, which were useful in developing "lessons learned" training materials. Understanding risk factors and dangerous situations, made more realistic by DHM visualizations, allows for both theoretical and realistic accident reconstruction and investigation. DHM makes it possible to exactly model human silhouettes, and reproduces detailed anthropometrical features of the humans involved in accidents.

43.11 Choosing the Right DHM Software and Motion Capture Hardware Systems

Finding the right software tool with all the features and capabilities to develop and execute computer code for virtual motions and behaviors is critical to any DHM research. Commercial DHM software tools provide a product with a virtual human modeling system for ergonomic analyses and work performance evaluations to help design and study mining systems with man-machine interactions. It would be prudent in early planning of using DHM that the correct research tools fit the immediate job and potential work for the future. The following points are for reference only, and do not take into account specific software uses, project scopes, or budget considerations.

Digital motion developed in DHM software is an approximation of actual human motions required to accomplish the task and usually results in rigid, robot-like movements. This animation is very time consuming, especially as you increase the number of virtual humans, and simultaneously, the number of joints involved. Conversely, motion capture systems deliver realistic motion data files generated quickly and easily from one motion capture session. Also, customizing the DHM user interface to implement graphical user interface (GUI) applications allows users to quickly develop and test user interface code without the need to write and compile complex code or work with abstruse "widget" libraries.

With increasing options, choosing which DHM and motion capture system will best suit one's needs is no easy task. Several factors will help determine the choice. Only some motion capture systems, for example, are real time. If one is looking for high-performance animation, the choices will narrow. If one needs a wireless system, that will limit choices as well. While motion capture systems don't come cheap, optical systems are definitely in the higher price range. Ensure that whichever motion capture system one chooses supports one's DHM—not all motion captures play well with all DHMs, and vice versa. Most high-quality DHM software will include a host of special features, but other features will add to the basic cost; plan well and choose soundly. All the DHM software and motion capture systems have their pros and cons, and there is no magic specification that measures the quality of data you can get from any one choice. Once the choices are narrowed, ask for sample data. Ask if one can take the DHM software and motion capture system for a test drive, that's even better. Some vendors will accommodate this request, so it's worth asking.

Add-on modules and devices available with DHM and motion capture could overwhelm the average researcher or scientist. Have an experienced vendor or representative give you a demonstration of these features, which are extremely helpful in understanding even the most challenging features. In addition, ask for references. Obtain a list of current and past users from the vendor. Customer feedback can be the most important decision-making aid, and gives one real-user perspective and *experience*—very helpful if you buy the same DHM or motion capture system.

Most vendors provide initial training when the product arrives, and technical support is usually free for the first year. Extending technical support is wise, and it's also recommended to seek training after one has a chance to "play" with the product, which may incur additional costs but in many cases is worth the expense. If one is able to attend additional training for the product, take specific problems, questions, and issues for discussion; use them as examples to practice new features. Take full advantage of the instructor, who should also play a consultant role to class participants during the training.

Maintaining yearly support and maintenance contracts usually includes updates to the vendor's software or firmware. Annual support and maintenance charges usually come as one package, but occasionally a vendor will offer different packages to cover limited support needs at a lower cost. There are plenty of support gurus out there. Look for one that provides the best support and explains issues and answers questions patiently and thoroughly within a reasonable response time via telephone, email, or in person.

Computer platforms and networking are important in the design of usage if one intends to share DHM and motion capture licenses and data files. Regardless, both systems require very large computer storage space and large data-streaming needs. It's recommended that one select scientific workstations with speed, storage, various media-recording capabilities, and various ports and slots to handle plug-ins and expansion needs.

Attending conferences that discuss and address DHM technology is an excellent resource to learn and share information. Usually, vendors of DHM software and motion capture systems attend conferences with exhibits, providing an opportunity to talk about needs and potential applications. In addition, conferences provide an exceptional opportunity to associate with long-time users of DHM and motion capture systems.

43.12 Looking to the Future

New generations of highly advanced virtual humans that reflect state-of-the-art technology are on the horizon. Whispers of what's to come are evidenced by Kim et al. (2005), Mi et al. (2004), Wang et al. (2005), Yang et al. (2004), and Zhou and Lu (2005). The next generation of DHM will come from current digital human model transformations and "newborn" DHMs. In addition to looking real, they will most likely include realistic gross movement and internal functions; autonomously predict postures and motions; monitor human performance indices including physiological and musculoskeletal quantities; provide valuable information pertaining to the efficiency and effectiveness with which a task is completed; exhibit cognitive behavior such as the ability to walk through a maze as the environment changes and discern which new path to take. These new DHMs will plug into motion capture systems, be easily inserted in a CAD environment, and deployed into vehicles, systems-maintenance settings, and hostile and hazardous areas.

As researchers use DHM systems to improve the safety and health of workers in hazardous environments, they should also look for improvements in DHM technology. Continued research incorporating the latest DHM advancements and features can only increase the effectiveness of DHM in improving, and ultimately saving, real human lives.

43.13 Mining Terms

Boom arm or roof-bolter arm: The arm is a roof-bolter appendage that vertically lifts the drill mast mounted to it and horizontally swings to adjust position for desired location of vertical lift.

Continuous haulage: A controlled mobile conveyor system that navigates in underground mines and moves coal from the working face to a main dumping point from which the coal is taken to the surface.

Continuous miner: A self-propelled machine that rips coal, metal, and nonmetal ores, rock, stone, or sand from the face and loads it onto conveyors or into shuttle cars in a continuous mining operation.

Entry: An entry is a horizontal mine passageway or room that is formed as a result of room-and-pillar mining operation. The passageway or room varies in height, width, and length, for example, 24 inches high, 16 feet wide, and 60 feet long or 15 feet high, 20 feet wide, and 120 feet long.

Face: The face is the working area in from the last open crosscut in an entry or a room. Crosscuts in room-and-pillar mining result from piercing of pillars at regular intervals for the purpose of haulage and ventilation.

Longwall: In longwall mining, a cutting head moves back and forth across a panel (longwall) of coal averaging 945 feet in width and 9,900 feet in length. The cut coal falls onto a flexible conveyor for removal. Longwall mining is done under hydraulic roof supports (shields) that are advanced as the seam is cut. The roof in the mined out areas falls as the shields advance.

Rib: In underground coal mines, it is the solid coal side of a passageway (entry).

Road header: An entry-boring machine, called a road header, which bores the entire section of the entry in one operation.

Roof: In underground coal mines, the rock immediately above a coal seam. Sometimes part of the coal is left for the roof.

Roof bolter: A machine to install roof support bolts in underground mine passageways or the one who operates this machinery.

Roof falls: This is when rock or coal falls from the roof into a mine passageway (entry).

Room-and-pillar: Most underground coal is mined by the room-and-pillar method, whereby rooms are cut into the coal bed leaving a series of pillars, or columns of coal, to help support the mine roof and control the flow of air. Generally, rooms are 16 to 30 feet wide and the pillars up to 100 feet wide. As mining advances, a grid-like pattern of rooms and pillars is formed.

Shuttle car: Diesel or electric-powered car in underground mine that transports materials from the working face to mine cars or conveyor belts.

Tramming: This term is used to define when the machine operator moves a self-propelled piece of equipment from place to place.

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