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Verification of a Roof Bolter Simulation Model

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Abstract

This paper presents the results of an effort to verify a simulation designed to investigate the safe speed range for the vertical movement of roof bolter boom- arm to reduce worker injuries in underground coal mines. The results of the laboratory investigations are being used to (1) determine input parameters unique to the mining environment and needed to develop a credible, computer-based, human-machine interactive model (2) confirm the model would accurately represent operator movements and positions while performing his tasks relative to the roof bolter and (3) determine which aspects of the procedure being simulated are most critical if hazard predictions are to be made from simulations using valid models of operators' behaviors and varying the machine appendage speed.

Background

In underground coal mines, a roof bolter is a machine that drills holes and inserts steel rods into the freshly exposed mine roof to control cave-ins. Roof bolting may be regarded as a fairly structured and repetitive work situation. Roof bolter operators have the job of drilling holes and installing bolts to secure sections of unsupported roof after miner crews have cut and removed a section of coal. A predetermined pattern for installing bolts is followed, as set forth in the mine's Mine Safety and Health Administration (MSHA) approved roof control plan. The entire bolting operation must be completed in a confined environment in the vicinity of moving machinery. The confined environment, typically 114.3-cm (45-in) to 182.8-cm (72-in) floor to roof heights, requires the operator to work in awkward postures and to perform tasks requiring quick reactions to avoid being contacted by the moving machine appendages. Further compounding the problem is the low lighting conditions found in mines and the restricted visibility due to the canopy (or Automated Temporary Roof Support) on roof bolters, which protects the worker from roof falls while working under an unsupported roof. These conditions combine to make roof bolting one of the most dangerous occupations in underground mining. For the years 1998 through 2001, the MSHA injury database showed there was an average of 638 roof bolter operator accidents per year in underground coal mines, representing 28% of all mining equipment accidents.

The main question needing to be answered is what range of boom speeds minimizes the roof bolter operators' chances of injury while still allowing the roof bolter operators to safely perform their job. This question becomes even more important in light of new rules proposed by MSHA to improve the design of roof bolters, which are awaiting completion of this simulation work. The factors to be considered are whole body and appendage motions and variation in movements (range of motions) of individuals performing bolting tasks in various postures and mine seam heights. Due to the confined environment of mining operations, the postures of bolter operators are unlike the postures of workers in other occupations. It is unknown what biomechanical effect restricted space has on operators' motions or their ability to perceive and avoid hazards. In spite of awkward positions and postures imposed on operators by their confined environment, they require quick responses to dangerous situations. In conducting the investigation, operator motions while performing roof bolting tasks and avoiding moving equipment associated with roof bolting were measured using Ascension's MotionStar® motion tracking system. The motion data was used to provide model information and later to verify the simulation.

EDS/PLM Solutions- Jack® software was the simulation tool chosen to develop a roof bolter model and operators for the roof bolting simulation. Jack® is a human-centric visual simulation software package. Jack®'s software architecture allows users to extend its simulation functionality by using code written with the LISP programming interface and the Jack Command Language (JCL). The roof bolter model came from code developed in LISP and JCL that created random human motion, random motion goals for the hands and torso, and random motion events reflecting operator's risky behaviors.

The uncertainty or randomness inherent in the drilling and bolting tasks must be incorporated into the model to effectively determine the likelihood of an operator being injured. To model the random motion, individual paths are made to differ slightly, even though the motions look very similar. Therefore, the model incorporates randomness of motion, path variance within that motion, and random risky behaviors [Klishis et al. 1993]. Thus, for a given machine and operator, the operator's various risky behaviors, motions for each risk behavior, motion paths associated with each motion behavior, and moving machine appendages have some degree of randomness. These random motions give the model a realistic representation of the operator's motions and behaviors during the performance of any machine task. A model that includes any random aspects must involve sampling for generating random variants. The phrase "generating a random variant" means to observe or realize a random variable from some desired arrangement of values of variables showing their observed or theoretical frequency of occurrence. To determine the range of these variations, motion laboratory tests were conducted using experienced roof bolting personnel.

Human Subject Test Methods

For the purpose of building a random motion simulation model of roof bolter-machine interactions, unique parameters were required [Ambrose 2000]. Generally, human motion parameters are measured by recording time to move a single body part in a straight line from a specific point A to a specific point B. This reaction time measurement was unsuitable for our modeling effort [Park et al. 2001]. The parameters required consisted of the range of operator motions, maximum velocities, and distances required for each of the tasks that must be performed in order to complete a bolting sequence. The measurements needed to be made with the whole body in motion, trying to avoid the machine appendage moving in three-dimensional space, and in a confined environment, where straight-line movement or even a single motion path was not practical for avoiding contacts [Badler et al. 1994] [Faraway, 1997].

The human motion testing was conducted using twelve subjects experienced in roof bolter operation from the local office of the United Mine Workers of America to accurately utilize the skills involved in operating mining equipment.

Human motion parameters were determined for the operator postures unique to operating a roof bolter. Two test scenarios were mimicked where roof bolter operators performed a complete roof bolting sequence in 114.3-cm (45-in) and 152.4-cm (60-in) seam heights from three unique kneeling postures. An additional test scenario was simulated with operators performing roof bolting tasks in a standing/stooping posture in a182.8-cm (72-in) seam height.

The human motions were captured and measured using the MotionStar® motion tracking system and recorded by a computer running the human motion-capture module in Jack®. Test subjects were asked to position themselves in representative bolt insertion positions with respect to a working wooden mockup roof bolter model (Figure 1) and perform roof bolting procedures as they would on the job. Due to the limitations of use of the MotionStar® motion tracking system around ferrous metals, a wooden mockup was constructed from plans provided by J. H. Fletcher & Co.; this mockup was an exact physical reconstruction of the original equipment.

Figure 1. Working wooden mockup roof bolter model

The roof bolting operation was broken down into specific tasks. The tasks and the amount of time spent on each task were observed [Klishis et al. 1993] and reported in a task analysis study on roof bolting. The task list was used in developing the experimental design for both the computer simulations and laboratory tests and to develop discrete movement scenarios for the computer simulation of roof bolting tasks using the Jack® simulation software. Using this information a computer-based simulation approach was developed to generate and collect contact data between the machine and its operators while dealing with many variables, such as the operator's response time, knee posture, choice of risk behavior, anthropometry, and machine appendage velocity.

Validation Questions Addressed

The accuracy of computer simulations is dependent on the validity of the input parameters. Input parameters can be validated only through the analysis of real world data. Models also require verification by comparing the model output to the scenario being modeled. Several questions needed to be addressed in order to obtain the data required for validation and verification: What is the expected outcome of the simulation and how well does it compare to empirical data? What are the important parameters in the simulation?

Verification Methods

Although it is not possible to completely validate a model and its results, it is possible to increase the level of confidence placed in them. The more tests performed in which it cannot be proved that the model is incorrect; the more confidence can be placed in the model [Robinson 1999].

The ideal method of verifying the model would be to have a direct comparison of the model's predictions of operator injuries and near misses (based on boom speed) and real-world data from actual occurrences of injuries and near misses in the mining industry. Unfortunately, industry data of this type is unavailable and laboratory testing that could potentially result in operator injuries cannot be performed. As the process outputs of this simulation as in most real-world systems and simulations was nonstationary and auto correlated, no statistical tests were directly applicable [Law et al. 1991]. The unavailability of this information is the reason the model needed to be developed initially. In the absence of data, which can be directly compared to the data produced by the simulation, an indirect method of model verification needed to be developed [Bartels 2001].

In the absence of readily comparable output data, two methods of model validation suggested by Law et al. [1991] were used: a face validity method (model seems reasonable to people knowledgeable about the system) and to test the assumptions of the model empirically. Since the variables of interest were random variables, the properties and functions of the random variables, such as means and variances, are of primary interest and were used to determine model validity [Sargent 1999].

The model should be validated relative to those measures of performance that will actually be used for decision making [Law et al. 1991]. To evaluate the validity of the simulation, decisions needed to be made to determine which aspects of the modeling effort were important to the outcomes the simulation was developed to measure. The initial purpose of the model was to predict the relative likelihood of the operator contacting the boom-arm based on the speed of the bolter boom-arm. Developing a model that accurately duplicates every aspect of an operation as complex as roof bolting would be a monumental task and is unnecessary when only certain aspects of the model are required to answer the questions the model was designed to address.

The model generated preliminary data that was studied to determine the important aspects of the simulation. The preliminary data was broken into segments corresponding to specific tasks involved with the bolting sequence. Only tasks that involved movement of the boom-arm were considered here, as a stationary object cannot strike an operator. Only the head, hands and knees were viewed as critical parts of the body that were likely to be struck by the bolter boom. The data was further divided by the part of the body for comparison to human subject test data.

The next challenge was to determine what the data needed to show in order to for the model to realistically predict the likelihood of operator making contact. First, the model had to accurately represent motions and processes involved in bolting. The sequence of tasks and speed of task completion had to be correct. Next, the random motion aspect of the model was critical to generation of contacts in the model. A contact is defined when two objects in the model interact and result in a touching. Random motions generated by the model had to be within the motion envelope and approximate the variation of movement of experienced human bolter operators.

Verification Outcomes

Two different verification methods were chosen to look at different aspects of the model. The first method was the traditional face validity evaluation by end users. A questionnaire was developed and distributed to manufacturers, bolter operators and mine inspectors. The responders were shown two animations: one was an actual operator produced from the MotionStar® motion capture data and the other was the virtual-operator in the simulation. The respondents were asked to compare aspects of the animations without knowing which was the actual and which the simulation was. Verification of the validity of the model was first implied when the responders agreed the simulation animations did not differ significantly from the animations of human operators.

The next verification technique was to compare the motions generated by the simulation with the motion data collected in human subjects testing. Although the predictions of the model could not be directly compared, the accuracy of the movements used to generate "contact data" could be. The aspects of operator movements determined to be critical were the range of motion of operators and variation in those movements.

Two sets of simulation data were generated. The first used virtual-operators with anthropometrical measurements identical to the twelve human subjects tested. Here, the data was compared on a subject-to-subject basis. The second set used Jack®'s generated operators in seven different anthropometric sizes. Data were compared to an average of the human subjects within a 10^{th}-percentile range, i.e. Jack®'s 55^{th}-percentile operator compared to average of subjects between 50^{th}- and 60^{th}-percentile ranges.

The human subject movement data tended to vary greatly from individual to individual (Figure 2) making it impractical for a direct comparison of each individual's exact path of movement. Since the amount of movement and the variation of movement were the primary concerns, the comparisons were made between the statistical range and standard deviation of movement.

Two sets of test data were developed to verify the model. One set compared a Jack® generated operators' motions in each of the anthropometrics size ranges with human subject data averaged for that range. The other set compared an individual test subject's motions with a simulation using that subject's anthropometry. Criteria for acceptance of the simulation data was <4-cm difference from the human subject data, selected because it represents the accuracy of the motion data collected (the static positional accuracy of the MotionStar® with the resolution settings used.)

Table 1 shows the percentage of range of motion data and standard deviations that met the acceptance criteria. The simulations run using average operators (Jack®-generated 25^{th}-, 45^{th}-, 55^{th}-, 65^{th}-, 75^{th}-, 85^{th}- and 92^{nd}-percentile persons) showed a greater percentage of values that met the acceptance criteria. This would be expected since averaged values were used as the input data for the simulation. In general, the percentage of agreement was good for modeling a scenario with the complexity of roof bolting. The range of variation between subjects was large and this range was incorporated into the model.

Figure 2. Variation of Movement for Two Subjects

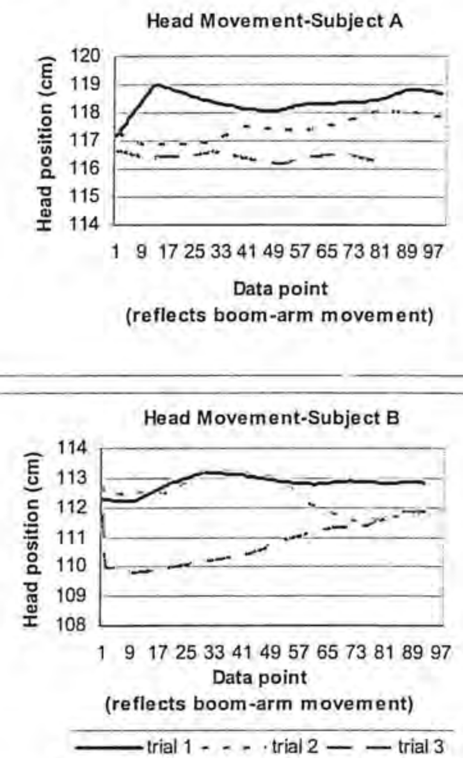

Table 1. Percentage Meeting Criteria

Posture	Condition	%Correct
Both Knees	152-cm (60-in) Seam Average	71.43
Both Knees	152-cm (60-in) Seam Subject	63.54
Right Knee	152-cm (60-in) Seam Average	71.07
Right Knee	152-cm (60-in) Seam Subject	62.29
Standing	182-cm (72-in) Seam Average	69.64
Standing	182-cm (72-in) Seam Subject	72.66
Starting Position	Average	80.35
Starting Position	Subject	72.22
Average		70.40

Conclusion

A computer-based, human-machine interactive model was developed that simulated the installation of roof bolts for the mining environment. The simulation model was based on input parameters established by conducting laboratory investigations using experienced personnel performing bolting operations with a model of a roof bolting apparatus. Two verification techniques were used to confirm that an acceptable level of confidence existed in the simulation's ability to accurately represent the motions and positions of human operators performing roof-bolting tasks. Responders from a face validity evaluation generally agreed that the simulation model did not differ significantly from the actions of experienced human operators. A comparison of statistical parameters for the range of motions of human and modeled operators showed an averaged correspondence above 68%. The final level of confidence in the model when direct output comparisons are not available is dependent on the confidence in the accurate selection of the significant parameters and their values.

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