From theory to practice: 
Designing for situation awareness to transform shovel operator interfaces, reduce costs, and increase safety

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ABSTRACT Mining equipment operators must interpret and respond to complex information delivered by technology-centric rather than user-centric systems. The ability to achieve high situation awareness (SA) in the face of this data overload is a key challenge to effective decision-making and information exploitation. Incidents attributed to human error that compromise safety and result in loss of revenue, or even life, are often the result of system designs that overload human cognitive capabilities. This paper defines SA as it relates to the operation of mining equipment and describes the design and preliminary evaluation of a new electric shovel operator user interface.

KEYWORDS Mining, Shovel, Situation awareness (SA), User interface design, Performance, Cost, Safety

RÉSUMÉ Les opérateurs d’équipements miniers doivent interpréter et répondre à des informations complexes provenant de systèmes centrés sur la technologie plutôt que sur l’utilisateur. Face à cette surcharge de données, la capacité d’avoir une connaissance élevée de la situation (CS) constitue un défi majeur pour la prise efficace de décisions et l’exploitation de l’information. Des incidents attribués à l’erreur humaine, pouvant compromettre la sécurité et engendrer une perte de revenus ou des pertes de vies, sont souvent le résultat de conceptions de systèmes qui surchargent les capacités cognitives humaines. Le présent article définit la connaissance de la situation en ce qu’elle a trait à l’opération des équipements miniers et décrit la conception et l’évaluation préliminaire d’une nouvelle interface pelle électrique-opérateur utilisateur.

MOTS CLÉS Exploitation minière, pelle, connaissance de la situation (CS), conception d’une interface-utilisateur, rendement, coûts, sécurité

INTRODUCTION
Mining operations involve multifaceted and often rapidly evolving situations that make it challenging to make critical decisions to solve emerging problems. Although advances in technology are enabling access to a greater variety of data, the deciding factor in successful operations depends on one’s ability to use the maze of available information promptly to support needed decision-making. The current mishmash of data and tools can easily exceed human cognitive limits and capabilities, and any errors or delays in processing the data to develop an understanding of its significance can easily undermine safety and productivity goals.

This paper focuses on defining situation awareness (SA) as it relates to modern mining operations and presents methods for improving SA in individuals and teams through a systematic approach for developing user-centric tools. This approach is based on a foundation of extensive research of SA during the past 25 years. SA-oriented design (SAOD) is a three-phase methodology that starts with goal-directed task analysis (GDTA) to identify operator information requirements, followed by a design phase to create user-centric system designs (Endsley & Jones, 2012). The last phase of SAOD is evaluation of the system based on SA measurement and other metrics. This methodology has been applied to electric rope shovel operators to help improve operator SA, performance, safety, and error rates. These tools and methodologies provide a strong foundation for improving SA in mining equipment operations.
BACKGROUND

Motivation

The biggest challenge within most industries is that the causes of accidents tend to be inappropriately categorized as “human error.” Such accidents typically occur under conditions that overload the human cognitive system. Human operators have difficulty integrating and processing information arriving from disparate systems while facing challenging operational scenarios. Technology-centric systems tax operator cognitive processes, reducing SA and performance and resulting in so-called “human error.”

Mining operations are not immune to this common challenge, given the many systems and human operators involved and the coordination required to maintain safety in high-performance mining operations. Developing and maintaining a high level of SA is the most difficult part of many jobs, especially during the operation of complex systems such as in the mining industry.

Situation awareness theory

Situation awareness can be thought of as an internalized mental model of the current state of the operator’s environment. This internal mental model forms the central organizing feature from which all decision-making and action takes place. Formally, SA is defined as “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” (Endsley, 1995). In other words, SA is being aware of what is happening around you to understand how information, events, and your own actions will affect your goals, both now and in the near future. Research indicates that SA is a fundamental construct driving human decision-making in complex, dynamic environments (Endsley, 1988, 1995; Endsley & Jones, 2012). The three levels of SA development (as illustrated in Figure 1) are described below:

- Level 1 SA (perception) involves monitoring, cue detection, and simple recognition leading to an awareness of multiple situational elements and their current states (e.g., location and status of the electric shovel and other equipment, shovel geometry, bench layout, terrain, and ore location and grade).
- Level 2 SA (comprehension) involves pattern recognition, interpretation, and evaluation to integrate elements and understand how this information will impact goals and objectives (e.g., is the truck loaded correctly and is it headed to the correct dump site).
- Level 3 SA (projection) is achieved through integrating Level 1 and 2 SA information and applying this information to the near future (e.g., if the shovel moves in this direction will it be in a collision path with another object; is my performance on track for reaching target quotas; what is the most effective way to move material).

METHODS

The SAOD process is a user-focused design methodology for computer systems based on SA theory. Using 50 distinct design principles that have been placed into functional categories such as complexity, automation, and alarm principles, SAOD provides a major advantage in developing effective system displays by directly addressing the issue of information content and how to optimize the presentation of that content for the user. As a key component of SAOD, the higher levels of SA (i.e., comprehension and projection) are directly supported via visual displays, significantly reducing unnecessary mental workload because the user does not have to piece this information together manually. SAOD is a three-phase process: (1) SA requirements analysis, (2) SA-oriented design, and (3) SA measurement (Figure 2).

Typically, SA requirements analyses have been conducted using a form of cognitive task analysis (Crandall, Klein, & Hoffman, 2006) known as GDTA (Endsley, 2000). GDTA involves in-depth knowledge elicitation from domain experts to identify the goals of a particular job class and define the decisions and information requirements for meeting each higher goal. This goal-oriented approach moves away from the consideration of basic task steps or processes and focuses on the operator’s cognitive requirements. The GDTA methodology has been used extensively to determine SA requirements in a wide variety of domains, including power systems, oilfield services, commercial aviation, and the military.
The SA design phase starts with an in-depth analysis of SA requirements, which feed directly into the design process as a key mechanism for developing information presentations that avoid high workload and increase SA. By applying the 50 SAOD principles, SA design • ensures that the key information needed for high levels of SA is included in each interface; • integrates the information in needed ways to support high levels of comprehension and projection of ongoing operations; • provides big-picture integrated information displays to keep global SA high, while providing easy access to details needed for situation understanding; • uses information salience to direct the user’s attention to key information and events; and • directly supports multitasking that is critical for SA. This is a significant addition to traditional human factors design and human-computer interaction principles, which aim at creating effective display designs by addressing surface features (such as legibility, contrast, and readability of information), human perception, and information processing (Mayhew, 1991; Wickens, Gordon, & Liu, 1998).

The third step in the SAOD process involves assessing the effectiveness of the designed system. Depending on project requirements and goals, SA, workload, performance, and usability measures can be used as metrics to evaluate the system. SA measurement provides a proven way to assess system effectiveness. There are several approaches for the direct measurement of SA. For example, objective and subjective SA measurement approaches include: • the SA behaviourally anchored rating scale and participant SA questionnaire (Matthews, Pleban, Endsley, & Strater, 2000); • the mission awareness rating scale (Matthews & Beal, 2002); and • the SA global assessment technique (SAGAT).

The SAGAT is a widely tested and validated technique for objectively measuring SA across all of its elements (levels 1, 2, and 3) based on a comprehensive assessment of SA requirements (Endsley, 2000). To administer the SAGAT, users are randomly queried with questions based on SA requirements. The results are compared to ground truth to assess user SA and indirectly measure system effectiveness in presenting relevant information to the user. SA measurements should be supplemented by workload, performance, and usability metrics and measurements to provide a comprehensive assessment of the target system’s capabilities and limitations in the context of user interaction.

APPLICATION

SA requirements analysis

A shovel operator SA requirements analysis was conducted using the GDTA methodology. As part of the GDTA, our team conducted knowledge elicitation sessions with 10 electric rope shovel operators. These sessions were conducted during visits to two open-pit mines: a copper mine in British Columbia, Canada, and a gold mine in Nevada, USA. Three operators were observed on the job (in the cab of electric shovels). The remaining operators were interviewed in an office environment, either individually or in pairs. During these interviews, the focus was on shovel operator goals, decisions, and SA requirements to understand the operator’s cognitive decision-making process. Discussions of operator preferences and the operating environment supplemented the interview sessions. Four operators had approximately 15 years of experience, whereas two operators were fairly new to the shovel operator position with less than six months of experience, but had previous experience using other equipment within the mining operation. The remaining operators had between six months and 15 years of experience. This experience mix enabled us to see a range of perspectives based on the experience level of the operator. The operators were familiar with a variety of P&H and Bucyrus electric rope shovels and their on-board systems. The resulting GDTA was validated in two sessions with four representative operators and subsequently revised. An excerpt of the final GDTA is shown in Figure 3.

In addition to the GDTA, an environmental analysis was conducted to identify additional requirements and constraints for the design phase. The environmental analysis focused on reach distances for touch controls, viewing distances for displays, shovel peripheral visibility, and general space availability in the cab. The outcome of this analysis, combined with the GDTA, was the recommendation of two high-resolution 35.5 cm displays for the shovel operator. The recommendation also included the need to support smaller screen sizes when cab space or peripheral visibility did not permit the placement of larger screens. In summary, it was determined that the resulting designs should be flexible and accommodate a variety of display sizes as well as landscape and portrait configurations.

SA design

The shovel operator user interface (UI) was designed by following the SAOD process (Endsley & Jones, 2012). For this design, our team combined human factors guidelines and principles with an analysis of the environment, as well as technology considerations, and designed the UI based on SA requirements analysis. A high-level layout of the shovel UI, with annotations of major UI regions, is shown in Figure 4.

The tab-based navigation scheme enables quick, one-click access to major functional areas. Supporting panels provide multitasking capability and support global SA. Control surfaces were designed larger than typical desktop UI controls to work with touch screens. Figure 5 shows two side-by-side screens from the shovel UI design: the virtual map and the multiview camera.
In general, the goal for this effort was to increase operator SA and reduce workload by designing a system that integrates key information elements according to the shovel operators’ cognitive model. Consequently, the shovel UI is expected to increase safety and reduce costs. For example, specific design features were developed to help avoid collision incidents, detect lost teeth, and minimize the routing of valuable ore to waste streams.

Collision incidents in mining operations are rare but costly events. The shovel UI incorporates multiple features to help reduce the chance of a collision incident by providing the operator with multiple windows into the surrounding environment (Figure 6):

- The virtual map visualizes shovel geometry and range of motion through overlays. This helps establish safe boundaries around the shovel.
- The virtual map presents the location of known (global positioning system-based) objects to increase the operator’s awareness of the surroundings.
- Objects detected by proximity sensors are fused with known objects (when available) and overlaid on the map.
An inset (top right in Figure 6a) provides a dedicated picture-in-picture view of known and detected objects, and can be made persistent by placing it in a supporting pane.

Multiple camera views show the surrounding environment and integrate proximity warnings for better alert saliency.

An always-present panel alerts the operator to significant events like proximity warnings.

An envisioned predictive collision avoidance system alerts the user to objects in shovel’s collision path by haptic feedback to the operator via the control joystick.

Lost teeth can result in significant operational delays and, if unnoticed, costly and dangerous repairs to crushers. Monitoring tooth health, detecting tooth wear and tooth loss, verifying loss, and taking corrective action is crucial to operations. The teeth monitoring panel presents the operator with relevant alerts regarding shovel teeth as well as shortcut controls to verify and take action in response to the alerts. The bucket camera, augmented with teeth alerts, can be automatically brought up to verify tooth health (Figure 7). When a tooth is missing, a dedicated screen helps the operator find the truck carrying the tooth as well as controls to locate and stop that truck for corrective action (Figure 8b).

Mistakenly routing valuable ore to waste streams can be a costly mishap, potentially costing hundreds of thousands of dollars when high-grade ore is involved. The shovel UI
provides direct support for error prevention, error detection, and error correction to minimize this type of incident. Multiple salient cues are provided to ensure the operator is aware of the material that is being dug up and loaded onto the haul truck and the correct destination dump site for the haul truck. To support error prevention, the truck destination is prepopulated based on the currently selected material and requires confirmation for manual override to reduce unintentional operator error. Error detection is supported on the virtual map by highlighting the current active material as well as what has been loaded on haul trucks. In addition, loading panels present the material code, assigned haul truck, and truck destination (Figure 8a). Error correction is supported by providing tools to contact a truck that may be headed to the wrong site and request an emergency stop (Figure 8b).
RESULTS
For the evaluation of this UI, four operators and two supervisors participated in two user reviews during which the designs were presented and rated via usability surveys. During the review sessions, the mining personnel were encouraged to provide feedback (both during the meeting and, for the operators, afterward as part of a post-action survey). All four operators had at least three years of experience. On the usability surveys, all the operators found the information presented on the displays to be relevant to their jobs, and either agreed or strongly agreed that the UI was easy to understand, the location of information was easy to remember, and the displays would make their jobs easier. Perhaps most importantly, all operators stated that they strongly agreed that the designs shown would help eliminate hazards to themselves, others, and their equipment. The surveys included basic demographic and background questions as well as ratings of aspects of the shovel UI. The shovel operators rated the designs on four distinct criteria:
• The UI is easy to read and understand.
• It is easy to remember where information is located on the UI.
• The UI would make my job easier.
• The UI would help eliminate hazards (to yourself, others, or equipment) that I experience currently.

The ratings were presented on a seven-point Likert scale (Likert, 1932), ranging from “strongly disagree (1)” to “strongly agree (7).” “Neutral (4)” represents a neutral response, whereas “strongly agree (7)” represents the best possible feedback on the Likert scale. For all four aspects of the UI, the shovel operators rated the design six (6) or greater, corresponding to high user satisfaction (Figure 9).

CONCLUSIONS
This paper explains, at a high level, the process used in the analysis, design, and evaluation of an electric rope shovel operator UI. The shovel operators that were surveyed were very receptive to this new design. In addition to the surveys, specific comments included “user friendly,” “easy to understand,” “higher level of safety achieved with information available,” “greater awareness of possible hazards,” and “great amount of information.” Survey results from the evaluation support these comments. Based on these preliminary results, we expect the implementation of the shovel UI will reduce costs and increase safety in mining operations through increased operator SA and performance. It should be noted that while encouraging, survey results are based on subjective ratings of only four shovel operators. We recommend further testing and evaluation of this design with a larger user base performing simulated or operational tasks to validate the findings. Objective measures of performance and SA should be used to empirically quantify the effects of the new shovel UI, especially compared to existing UIs.

While the results shown in this paper provide evidence of what SAOD can do for shovel operations, they also provide an idea of how this approach could benefit other types of sub-operations within mining, particularly tasks requiring coordination and communication between multiple parties to be effective. Future work should expand the approach outlined here and apply it to other aspects of mining operations.
mining, such as dispatch control, maintenance, drilling, and vehicle operations beyond the shovel.

ACKNOWLEDGMENTS

This work was funded by the Global Mining Standards and Guidelines Group (GMSG). We thank Barrick Gold Inc. and Teck Resources Limited for their support throughout this project and for providing access to mining sites and electric shovel operators.

Paper reviewed and approved for publication by the Surface Mining Society of CIM.

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