FROM THEORY TO PRACTICE: HOW DESIGNING FOR SITUATION AWARENESS CAN TRANSFORM CONFUSING, OVERLOADED SHOVEL OPERATOR INTERFACES, REDUCE COSTS, AND INCREASE SAFETY

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ABSTRACT

Mining operators are faced with 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 for effective decision making and information exploitation. Incidents that result in loss of revenue and even life, and compromise safety that are attributed to human error are often the result of system designs that overload human cognitive capabilities. This paper focuses on defining SA as it relates to mining operations and presents methods for improving SA through a scientific approach for electric shovel operator user interface development.

KEYWORDS

Mining, Shovel, Situation Awareness, User Interface, Design, Performance, Cost, Safety

INTRODUCTION

Mining operations involve multi-faceted, distributed and often rapidly evolving, distributed 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 for successful operations depends on people's ability to rapidly capitalize on the maze of available information 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 our goals in this domain.

This paper will focus on defining situation awareness (SA) as it relates to modern mining operations and will present methods for improving SA in individuals and in teams through a systematic approach for developing user-centered tools that is based on an extensive research foundation on SA over the past 25 years. Situation awareness-oriented design (SAOD) is a 3-phase methodology that starts with goal-directed task analysis (GDTA) to identify operator information requirements, followed by a design phase to create user-centered system designs. 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 reduce errors. These tools and methodologies provide a strong foundation for improving SA in mining 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 pouring from disparate systems while facing significant challenges. Technology-centered systems tax operator cognitive processes reducing SA and performance, and resulting in so-called 'human error'.

Mining operations are not immune from this common challenge, given the many systems and human operators involved, and the delicate 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 and most certainly in the operation of complex systems such as in the mining industry.

Situation Awareness Theory

SA 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 formation (as illustrated in Figure 1) are described below:

- Level 1 SA (perception) is the processes of monitoring, cue detection, and simple recognition, leading to an awareness of multiple situational elements and their current states (e.g., location of the electric shovel and other equipment, shovel geometry, ore location and grade, etc.)
- Level 2 SA (comprehension) is the processes of pattern recognition, interpretation, and evaluation to integrate elements to understand how this information will impact goals and objectives (e.g., is the truck loaded correctly and is it headed to the right dump site)
- Level 3 SA (projection) is achieved through integrating Level 1 and 2 SA information and projecting this information into 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, etc.)

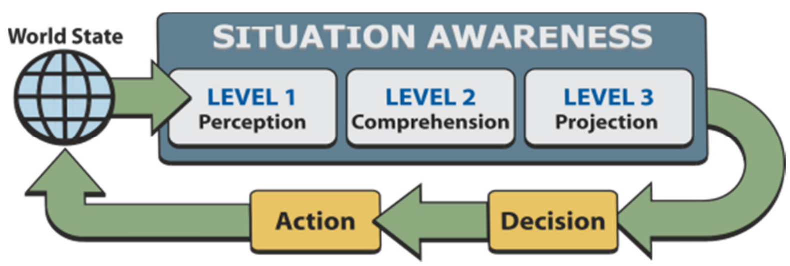

Figure 1 – High-level model of SA showing the three stages of SA formation leading to decision and action

METHOD

The SAOD process is a user-focused design methodology for demanding systems based on SA theory (Endsley & Jones, 2012). Utilizing 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 on visual displays, significantly reducing unnecessary mental workload required for the user to piece this information together manually. SAOD is a three-phase process: (1) SA requirements analysis, (2) SA design, and (3) SA measurement (as illustrated in Figure 2).

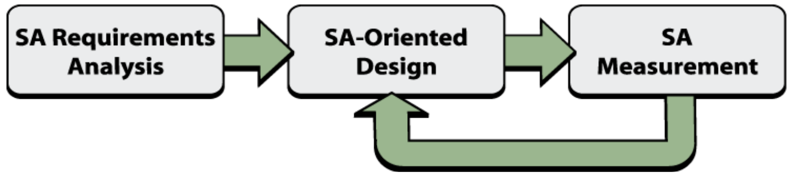

Figure 2 – SA-oriented design is a three-phase methodology for optimizing operator SA (Endsley & Jones, 2012)

Typically, SA requirements analyses have been conducted using a form of cognitive task analysis (Crandall, Klein, & Hoffman, 2006) known as GDTA (Endsley, 2000). The GDTA involves in-depth knowledge elicitation with domain experts in order to identify the goals of a particular job class, and to define the decisions and information requirements for meeting each higher goal. This goal-oriented approach moves away from 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 operations including power systems, oilfield services, commercial aviation, and the military domain.

The SA design phase starts with an in-depth analysis of SA requirements feeding directly into the design process as a key mechanism for developing information presentations that avoid high workload and maximize SA. By applying the fifty SAOD principles, SA design (1) ensures that the key information needed for high levels of SA is included in each interface, (2) integrates the information in needed ways to support high levels of comprehension and projection of ongoing operations, (3) provides big picture integrated information displays to keep global SA high, while providing easy access to details needed for situation understanding, (4) uses information salience to direct the user's attention to key information and events, and (5) directly supports multi-tasking 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, 2001; Wickens, Gordon, & Liu, 2004).

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. When feasible, objective SA measures provide a proven way to assess user SA levels and thus system effectiveness. For example, the Situation Awareness Global Assessment Technique has been successfully used to provide this information by directly and objectively measuring operator SA (Endsley, 2000).

APPLICATION

SA Requirements Analysis

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. 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 on personal preferences and the operating environment supplemented the interview sessions. Four operators had approximately 15 years of experience whereas 2 operators were fairly new to the shovel operator position with less than six months of experience, but had previous experience within the mining operation with other equipment. Remaining operators had between 6 months and 15 years of experience. This experience mix enabled us to see a variety of perspectives, based on the experience level of the operator. The resulting GDTA was validated in two sessions with 4 representative operators and subsequently revised. An excerpt of the final GDTA is shown in Figure 3.

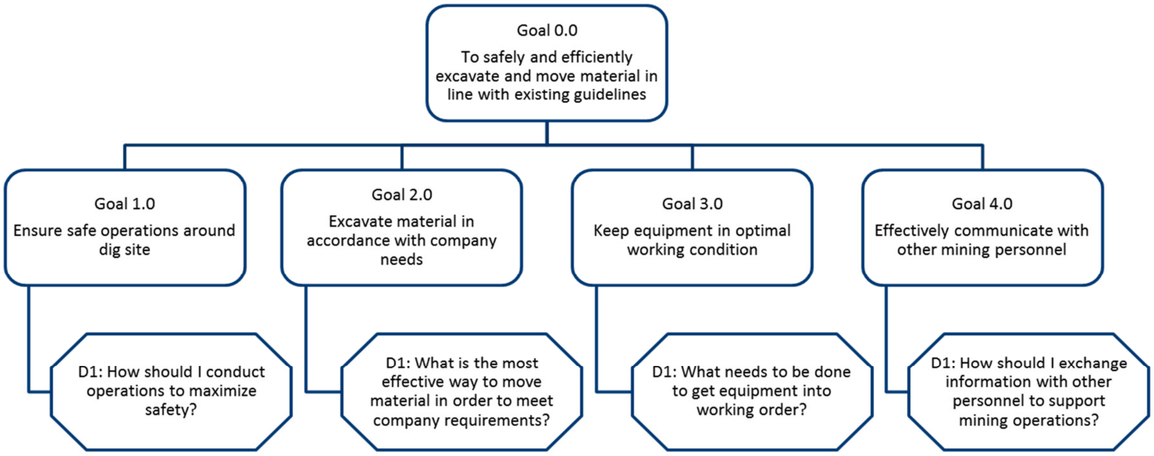

Figure 3 – An excerpt from the electric rope shovel operator GDTA showing top level goals and decisions (SA requirements not shown)

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 surfaces, viewing distances for displays, shovel peripheral visibility, and in 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 didn't 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.

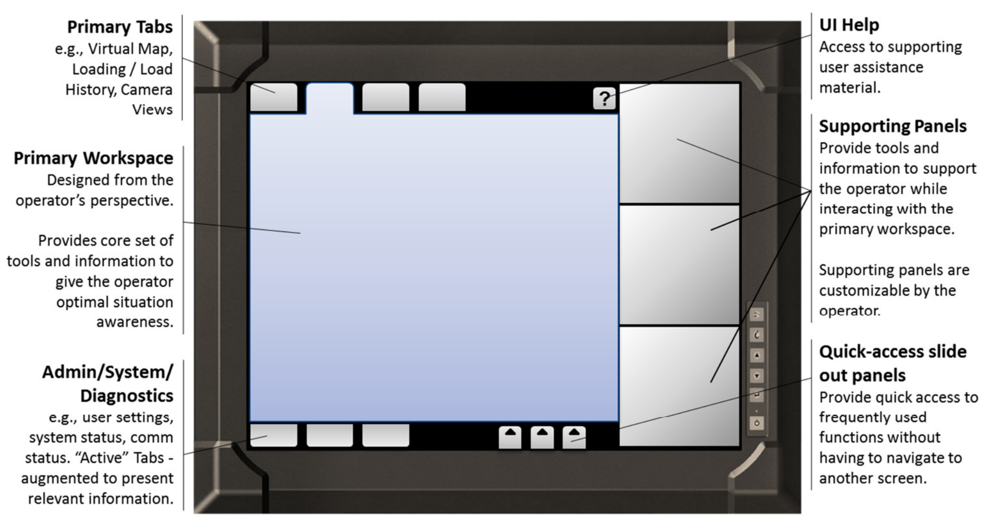

Figure 4 – A high-level layout of the shovel UI with explanations of major regions

The tab-based navigation scheme enables quick, one-click access to major functional areas. Supporting panels provide multi-tasking 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. On the left is the virtual map. On the right is the multi-view camera.

Figure 5 – Two screens (virtual map on the left and camera views on the right) from the Shovel UI. Compared to stove-piped systems, these screens fuse and integrate information from multiple sources to reduce operator workload and increase SA

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 operator's 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).

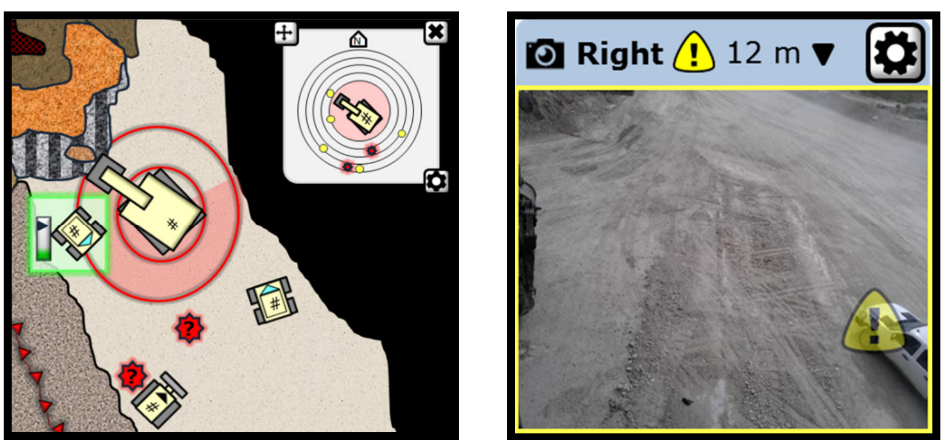

Figure 6 – Multiple UI features alert the operator to the presence of nearby objects

- 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 6) 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 as the operator is commanding the shovel via a joystick.

Lost teeth can result in significant delays in operations, and if unnoticed, costly and dangerous repairs to crushers. Monitoring tooth health, detecting tooth wear, 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 on 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 8, right).

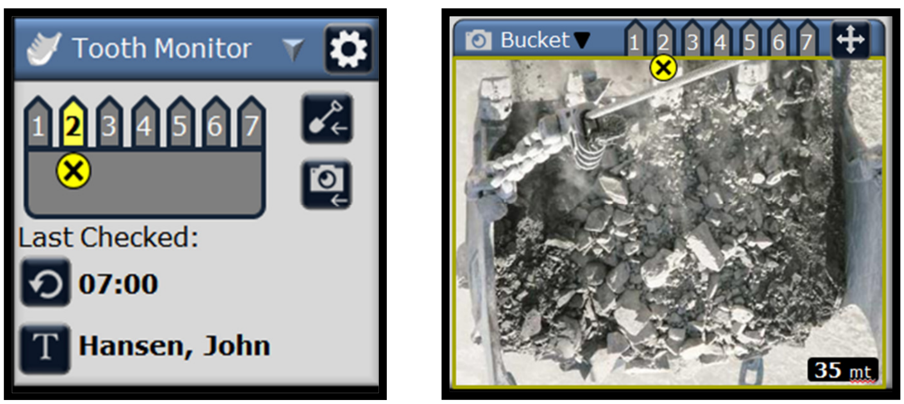

Figure 7 – Teeth monitoring panel and bucket camera are shown with integrated tooth alerts

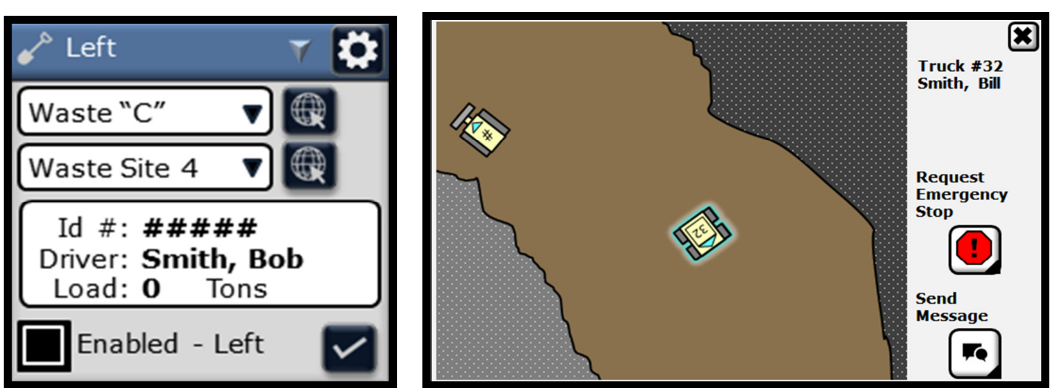

Figure 8 – The shovel UI provides multiple cues to keep the operator SA high and minimize the possibility of routing valuable ore to waste streams

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 (1) error prevention, (2) error detection, and (3) error correction to minimize this type of incidents. 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, truck destination is pre-populated based on the currently selected material and requires confirmation for manual override to reduce unintentional operator error. Error detection is supported on the 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 8, left). Error correction is supported by providing tools to contact a truck that may be headed to the wrong site and request emergency stop (Figure 8, right).

RESULTS

For the evaluation of this UI, a total of four operators and two supervisors participated in two user reviews where 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, the operators all found that 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, that the location of information was easy to remember, and felt that 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:

1. The UI is easy to read and understand.
2. It is easy to remember where information is located on the UI.
3. The UI would make my job easier.
4. The UI would help eliminate hazards (to yourself, others, or equipment) that I experience currently.

The ratings were presented on a 7-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 above, corresponding to high user satisfaction (Figure 9).

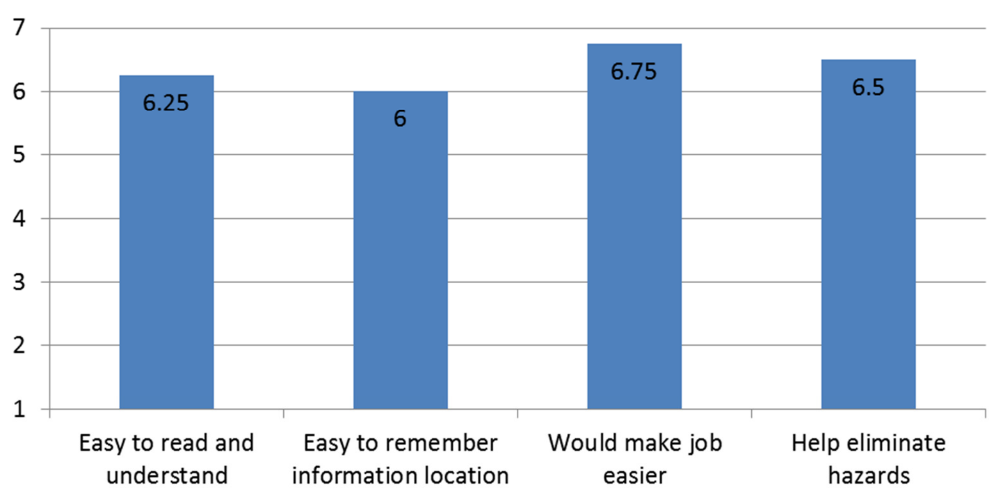

Figure 9 – Users rated aspects of the design on a 1–7 Likert-scale, with all 4 measured aspects of the UI scoring 6 or above

CONCLUSIONS

This paper explained the process used in the analysis, design, and evaluation of an electric rope shovel operator UI. Shovel operators were very receptive to this new design. Specific shovel operator 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.

We recommend further testing and evaluating these designs with simulated or operational tasks to further validate the findings and provide any additional improvements. Also, 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 mining operations, as many tasks require 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 like dispatch control, maintenance, drilling, and vehicle operations beyond the shovel.

ACKNOWLEDGEMENTS

This work was funded by the Canadian Institute of Mining (CIM) Mining Standards and Guidelines Committee (MSGC). We would like to 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.

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