Collision avoidance and semi-automation in electric rope shovel operation

Steven Cloete¹ and Tim Horberry²

¹ Queensland Rail, previously SMI-MISHC, University of Queensland, Australia
² SMI-MISHC, University of Queensland, Australia

Abstract

Background: Electric rope shovels are large mobile excavators used in surface mining operations. The role of the shovel is to remove overburden from an underlying coal seam. Material excavated from the face is loaded into haul trucks for removal.

Aims: The objective of this research was to apply human factors techniques and principles to the evaluation and iterative design of load assistance and collision avoidance technologies for electric rope shovels.

Method: Following observations, interviews and technical data reviews, a comprehensive hierarchical task analysis for shovel operation was developed. The human reliability technique, HEART, was used to examine where the shovel operation task could fail, and hence where there was most need for technology to support the shovel operator. The resultant needs analysis was then compared to the capabilities of the technologies under development.

Results: The HEART revealed task difficulties at several points of the operation cycle, and the technologies under development offer a good solution to human error potential in the shovel operation task. The modelling capabilities of the technology can be exploited to provide a shared in-cabin display, depicting the position of the truck relative to the shovel and an optimum ‘loading zone’.

Conclusions: Semi-automation and collision avoidance technologies under development have the potential to improve productivity and safety in electric rope shovel operation. The user-centred approach employed by the research is proving useful for the design new mining technologies, and further work will explore deployment and operator acceptance issues with a similar approach.

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Background

Over the past 150 years, mechanisation has been steadily introduced into the global mining industry. In all but the most basic mining operations, one of the outcomes is that many current mining activities have largely moved from manual to mechanised tasks¹. In the past ten years, however, another change has been taking place in this domain: the increasing uptake of mining automation and ‘smart’ technologies. Currently, in many areas of mining and minerals processing, new technologies and automation are increasingly being designed and deployed². The ongoing imperatives for both safe and efficient workplaces have been the major drivers for the introduction of these technologies. However, such new technologies or automated systems for many mining processes and tasks have often seen them being deployed in workplaces as the technical systems becomes available, without them being systematically designed, integrated into work environments and evaluated from a user-centred perspective⁴.

Just as mining mechanisation did not completely remove the need for manual tasks, automation of mining equipment does not remove people from the mining system - it merely changes their roles¹. To ensure successful implementation of a new mining system which incorporates automation or smart technologies, it is essential to undertake a systematic analysis of the roles to be played by people in the new system and ensure that these roles are consistent with the capabilities and limitations of people, and that the system design (particularly the interfaces provided) optimise performance of these roles⁴. The work presented here is a first step along that path.

Other domains, such as aviation or defence, have undertaken considerable research and development work to achieve good human system integration. Perhaps the main conclusion from these comparable domains is that, to be successful, new technologies must meet the requirements of the job or task, work in emergency or abnormal operational states, support operators, and be acceptable to the eventual end-users⁷. However, the design of new technologies in the minerals industry has proceeded primarily from a technology-centred perspective, rather than first assessing the needs and what safety benefits they might bring¹. The non-mining literature is replete with cases of new technology failures⁶. These range from devices being badly integrated, not coping with excursions from normality, irrelevant for tasks, displaying unnecessary information, not accepted by operators or being overly relied upon⁸. Human factors issues with new technologies are thus of key importance, but are often not considered in sufficient detail when either designing or deploying these devices in mining.
Electric Rope Shovels

The focus of this research was upon electric rope shovels (referred to simply as shovels hereafter). Shovels are large, electrically powered mobile excavators used in surface mining operations (Figure 1). They are controlled by a single operator from an eccentric internal cabin, located to the right of the shovel’s boom and dipper. In coal mining, the role of the shovel is to remove top soil and overburden from an underlying coal seam, operating on a vertical material face up to 16 metres high. Material excavated from the face is then loaded into haul trucks for removal. Loading is frequently conducted on both sides of the shovel (offside loading refers to situations in which the truck is located on the left hand side of the shovel), although operating procedures vary from site to site, with some sites allowing onside loading only.

Figure 1. P&H 2100 BLE Electric Rope Shovel (with TruckShield and AutoLoad prototypes installed) and Volvo Haul Truck at Brisbane City Council’s Bracalba Quarry. P&H 4100 Series shovels commonly used in surface mining operations are approximately twice as large as this machine.

Shovels have generally become larger and more reliable\(^1\), but the engineering and control philosophies, as well as the methods of operation, have remained essentially the same for over 60 years. New technologies are, however, being developed for shovel control. This research explored the human factors issues with two prototype technologies developed by CRC Mining and P&H/Joy Global; a semi-automated load assistance system (AutoLoad) and a collision avoidance system (TruckShield). Both technologies rely on three independent methods of estimating the position of the haul truck relative to the shovel, using inertially-aided Global Positioning System (GPS), Ultra Wideband (UWB) ranging receivers and 3D scanning lidar\(^{10}\).

AutoLoad comprises a semi-automated load assistance protocol, intended to take control of parts of the shovel’s operation cycle in which the moving payload (i.e., loaded dipper) is in close proximity to a haul truck. After the operator has completed digging, AutoLoad swings the loaded dipper over a waiting haul truck, deposits the load and returns the dipper to a neutral pre-digging position. TruckShield is a collision avoidance protocol, designed to prevent metal-to-metal contact between the shovel bucket and the haul truck. It works by predicting the trajectory of the dipper over a two-second window and rapidly activating the hoist control (i.e., lifting the dipper up) if a collision is predicted. It can take effect during manual shovel operation or as an integral part of AutoLoad (AutoLoad cannot function if TruckShield is non-operational). Manual control can be resumed at any time during an AutoLoad cycle by depressing a ‘deadman’ pedal, but TruckShield, once actively avoiding a collision, does not allow operator veto.

The aim of the present research was to assist in the development process to ensure that the resultant systems were sufficiently well integrated with the needs and capabilities of human operators. To this end, an operator-centred gap analysis of manual shovel operation (i.e., operation without any operator assistance technology) was conducted, which comprised a variety of research methods including observations and interviews, hierarchical task analysis\(^{11}\) and application of the Human Error Analysis and Reduction Technique, or HEART\(^{12,13}\).

Method

Subject Matter Experts

Two Shovel Operator Trainers, each with a minimum of 15 years of operation experience, were engaged as subject matter experts. Their contributions were:

1. Demonstrations of best-practice manual shovel operation at a non-production testing site (Brisbane City Council’s Bracalba Quarry);
2. Training the first author in elementary aspects of shovel operation;
3. Participated in semi-structured interviews and technical discussions with the human factors and technology development teams;
4. Assistance with the construction and verification of a Hierarchical Task Analysis model; and
5. Assistance with the HEART analysis.

A total of six operators, all male, with shovel operation experience ranging from four months to fifteen years, participated in observations and informal interviews at three production sites, which are not identified for confidentiality reasons. Informed consent was obtained prior to all research activities. Ethics approval for this research was obtained from the University of Queensland ethics committee.

Semi-structured interviews

Opinions of the subject matter experts were sought on a number of topics, principally their perceptions of task difficulties in shovel operation, avenues for human error, the potential of the AutoLoad and TruckShield technologies to address human error, and issues of usability and operator acceptance.
Production site observations and interviews

Three central Queensland coal mines were visited by the first author in December 2012. These were production sites so research activities were limited to observations and informal interviews, both of which were conducted from within the shovel cabin. The aim of these exercises was to get an understanding of individual differences in operating style, interactions between the operators and pit crew (haul truck drivers and wheel dozer/grading operators), and operator’s opinions and experiences of the introduction of new technologies. There were good opportunities to discuss the latter, because two of the three sites were trialling a related collision avoidance method designed to prevent dipper contact with shovel tracks. The researcher accompanied the operators in the shovel cabin for periods ranging from 30 minutes to six hours, all during daytime shifts. A range of different operating conditions, face compositions and conditions, dig and loading patterns, operating styles and levels of operational experience were observed.

Hierarchical Task Analysis and HEART

A detailed Hierarchical Task Analysis (HTA) of manual shovel operation was conducted, using a seven-step procedure advocated by Annett[3]. Following recent successful work by Ward et al using both HTA and HEART[4], major subtasks of the HTA were then subjected to a HEART analysis[2,3] with the assistance of subject matter experts. For reasons of space, a simplified presentation of the HTA is presented in the present work.

Results

Observations and interviews

A range of viewpoints concerning task difficulty, error potential and technological interventions were put forward by the operators. Visibility with off-side loading (i.e., when the truck is located on the left-hand side of the shovel, opposite the operator cabin) emerged as one of the operational difficulties which operators felt increased the probability of dipper-truck collisions, whilst dig planning and face management were nominated as among the most cognitively demanding aspects of operation. Four of the six operators have had opportunities to work with the existing TrackShield protocol at various stages of its development, testing and deployment. Their opinions give reasonably strong indications that TrackShield and AutoLoad will face operator acceptance challenges. However, two of the more experienced, senior operators showed the greatest understanding of recognition of human error potential, and were generally positive and enthusiastic about the prospect of supportive technologies. The comments of one operator suggested that the introduction of AutoLoad would remove one of the more interesting and challenging aspects of operation, and that boredom and job dissatisfaction would result. In addition, comments from some of the operators suggested that personality factors and motivation may be strong determinants of acceptance; shovel operation is a coveted and competitive position in surface mining and pressure to maintain work performance is high. Therefore, even transient disruptions to the status quo by changing standard operating procedures or introducing new technologies are likely to meet with acceptance challenges.

HTA and HEART analyses

The HTA analysis did not address overarching surface mining philosophies, approaches, or techniques – simply the operation of a shovel for the purpose of excavation and removal of coal seam overburden. Although the operator's task does extend to supervision and monitoring of the work environment (e.g., management of other vehicles' work schedules in the pit), the analysis was constrained to the simple task of excavation. This overall goal was broken down into two subordinate goals – changing the position and orientation of the shovel, and excavation/removal of material. The latter comprises the operational tasks at which AutoLoad and TrackShield are active. These tasks are best described by a cyclical process (the ‘Digging Cycle’), which novice operators are trained to adhere to[5]. The application of the HEART was restricted to the major subtasks of the digging cycle, which were further decomposed in the HTA (although for reasons of space these higher levels of analysis are not presented here). The hierarchical structure of the task is depicted in Figure 2, and the Nominal Likelihood of Human Error values calculated in the HEART analysis in Figure 3. Further details of the HEART analysis, including Error-Producing Conditions (EPCs) and assessed proportions-of-effect, are shown in Table 1.

Figure 2. HTA diagram for manual shovel operation, depicted at the level of major subtasks.

The HEART revealed the greatest error potential for Dig Preparation, which requires precise positioning and control of the shovel’s dipper. The error potential is high for this task because of the limited field-of-view from the shovel cabin and the proximity of the dipper to the shovel’s tracks, which can easily be impacted when the operator is attempting to achieve optimum positioning of the dipper. The consequences of errors associated with Dig Preparation, however, are limited to cumulative equipment damage and operational inefficiencies. The Swing and Dump phases of the dig cycle – which is where
the TruckShield and AutoLoad technologies take effect – had the next highest potential for human error, respectively. By contrast, these subtasks have the potential to cause death or severe injury. This can occur during the Swing phase, by impacting the truck with a loaded dipper carrying in excess of 120 tonnes of material. Offside loading, during which the truck is not visible to the shovel operator, was noted by the subject matter experts as potentially more problematic, but for reasons of space no distinctions were made between onside and offside loading.

Impacts can also occur during the Dump phase, whereby the dipper’s load is improperly released (from too great a height or over the truck’s headboard - an armoured section of the haul truck’s tray directly above the driver’s seat). The EPCs contributing notably to error potential in the Swing and Dump subtasks were unfamiliarity, time shortage, poor feedback (due to obstructed or insufficient field-of-view and mechanical lags) and inexperience. This is consistent with the highly skilled visuomotor nature of the overall shovel operation task, and to a lesser extent the general consistency and predictability.

Figure 3. Values corresponding to Nominal Likelihood of Human Error, calculated for each of the major subtasks in the HTA.

<table>
<thead>
<tr>
<th>Error Producing Conditions (EPCs)</th>
<th>Description</th>
<th>Assessed proportion-of-effect for HTA Subtasks (Nominal Human Error Probability = 0.0004)</th>
</tr>
</thead>
<tbody>
<tr>
<td>unfamiliarity</td>
<td>Unfamiliarity with a situation which is potentially important but which only occurs infrequently or which is novel</td>
<td>1.16 4.20 3.40 1.00 2.60 4.20 2.76</td>
</tr>
<tr>
<td>time shortage</td>
<td>A shortage of time available for error detection and correction</td>
<td>1.10 2.00 1.10 6.00 2.00 2.00 2.37</td>
</tr>
<tr>
<td>low S/N</td>
<td>A low signal-to-noise ratio</td>
<td>1.90 1.00 1.90 1.00 1.00 1.00 1.30</td>
</tr>
<tr>
<td>features override</td>
<td>A means of suppressing or overriding information or features which is too easily accessible</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
</tr>
<tr>
<td>incompatibility</td>
<td>No means of conveying spatial and functional information to operators in a form which they can readily assimilate</td>
<td>1.70 1.00 1.00 1.00 1.00 1.00 1.12</td>
</tr>
<tr>
<td>model mismatch</td>
<td>A mismatch between an operator’s model of the world and that imagined by the designer</td>
<td>1.00 2.40 1.00 2.40 1.00 1.00 1.47</td>
</tr>
<tr>
<td>irreversibility</td>
<td>No obvious means of reversing an unintended action</td>
<td>1.07 2.75 1.07 1.07 1.70 2.75 1.74</td>
</tr>
<tr>
<td>Channel overload</td>
<td>A channel capacity overload, particularly one caused by simultaneous presentation of non-redundant information</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
</tr>
<tr>
<td>technique unlearning</td>
<td>A need to unlearn a technique and apply one which requires the application of non-redundant information</td>
<td>1.05 1.50 1.50 3.50 2.25 1.00 1.80</td>
</tr>
<tr>
<td>knowledge transfer</td>
<td>The need to transfer specific knowledge from task to task without loss</td>
<td>1.00 1.60 1.40 1.00 1.00 1.00 1.17</td>
</tr>
<tr>
<td>performance ambiguity</td>
<td>Ambiguity in the required performance standards</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
</tr>
<tr>
<td>risk misperception</td>
<td>A mismatch between perceived and real risk</td>
<td>1.15 1.30 1.75 1.00 1.00 1.00 1.20</td>
</tr>
<tr>
<td>poor feedback</td>
<td>Poor, ambiguous or ill-matched system feedback</td>
<td>1.00 1.50 1.00 3.00 2.00 1.20 1.62</td>
</tr>
<tr>
<td>poor cue</td>
<td>No clear direct and timely confirmation of an intended action from the position of the system over which control is to be exerted</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
</tr>
<tr>
<td>inexperience</td>
<td>A newly qualified operator, but not an expert</td>
<td>1.05 1.80 1.80 1.80 1.80 1.80 1.68</td>
</tr>
<tr>
<td>impoverished information</td>
<td>Quality of information conveyed by procedures and person to person interaction</td>
<td>1.00 1.00 1.00 1.00 1.00 1.00 1.00</td>
</tr>
</tbody>
</table>

Table 1. Error Producing Conditions and corresponding assessed proportions-of-effect for each HTA subtask. The average values for proportion-of-effect reveal that unfamiliar situations and time shortages are the strongest EPCs across all subtasks.
of operation, which led to relatively high assessments for unfamiliarity across all of the subtasks. The prominent EPCs for the swing and dump subtasks are effectively removed with AutoLoad and TruckShield working in concert, and potentially attenuated during manual operation with TruckShield activated. The analysis therefore suggests that the prototype technologies offer a sound solution to the problems operators could experience, as long as issues of operator acceptance, usability and other issues can be properly anticipated and dealt with.

In addition, converging evidence from all the data collection methods indicated that both haul truck drivers and shovel operators could benefit from a shared, real-time in-cabin display depicting the position of the haul truck (and other vehicles in the pit fleet) relative to the shovel. Drivers and operators both rely on visual cues for truck positioning for optimal loading, which can be difficult in dusty conditions or at night. Such a display could leverage the sensing and modelling capabilities already used by the TruckShield and AutoLoad systems in a relatively straightforward manner.

Discussion

Summary of major findings

The research activities completed indicate that the TruckShield and AutoLoad technologies offer a good fit to some of the more difficult and error-prone aspects of shovel operation. Taken together, the present findings suggest that TruckShield and AutoLoad have the potential to address some of the identified avenues for serious human error in the Swing and Dump subtasks. The need for technologies to support operators in tasks that are particularly prone to human error is strongly in agreement with the recent human error is strongly in agreement with the recent human error to support operators in tasks that are particularly prone to human error.

Limitations

The greatest limitation to any user-centred design investigation, especially in mining, is sufficient access to end-users. Difficulties in eliciting the cooperation of participants was due to the very small and geographically constrained population of shovel operators, the politically and organisationally sensitive nature of safety in the mining context, and the economic realities of the industry. Furthermore, conditions attached to institutional ethical clearance limited the nature and extent of data collection activities. Potentially insightful methodologies did not form part of the research exercise, including the Critical Decision Method (an in-depth knowledge elicitation technique aimed at understanding previous accidents, incidents and near-misses), collection and link analysis of in-cabin video recordings, and audio recordings of production activities and interviews/discussions. In sum, relatively few production site operators contributed to the research, and the depth of their input, although of key importance, was constrained.

Recommendations for further research and development

There is considerable scope for further research into semi-automation and collision avoidance technologies for mining in general, and the protocols which have been the subject of this research in particular. Two themes which we believe would provide the most fertile ground for future research endeavours are discussed below.

Operator Acceptance

Given the general lack of an operator-centred focus in the development and deployment of new mining technologies, it is perhaps no surprise to note that there are few systematic and widely-used measures to optimise operator acceptance of such technologies. Operator acceptance is of key importance because if such technologies are unacceptable to operators, they will not use them at all or at least not use them in the manner intended by the designer. In either of these cases they are unlikely to have the intended safety or performance benefits.

As noted by Stevens, Horberry and Regan, possible approaches to design and deploy technology to maximise acceptance may include:

- **Design**
  Understanding operator requirements, employing a user-centred iterative design framework, using best-practice HMI information, consider site cultural differences and wider regional factors in HMI design, employing a safe design and/or participatory design process and designing for a positive emotional experience.

- **Deployment**
  Consider regulatory/policy factors, equipping operators with sufficient skills and training, emphasising the benefits of correct system use, employ monitoring, giving timely/accurate feedback, giving operators prior awareness of what the technology can and cannot do and, considering the wider organisational/social use context.

Longer-term behavioural changes

Shovel operation is, in many ways, a simpler task than piloting an aircraft or monitoring a complex supervisory control system, and it is in these domains that the majority of long-term consequences of automation have been studied. Nonetheless, there is a sufficient body of literature to guide predictions on how TruckShield and AutoLoad may impact long-term behavioural changes, and these predictions could be confirmed by a targeted, post-deployment research exercise.

- **Automation-induced complacency**
  Aspects of the shovel operation task that require continual monitoring, such as face condition, are not affected by TruckShield and Autoload, so problems associated with complacency in monitoring are not particularly relevant.

- **Mental workload**
  A more plausible consequence of these technologies, particularly AutoLoad, is the reduction in operator’s mental workload to the extent that performance on
the remaining manual portions of the task can become adversely affected. This has been well documented in studies of passenger vehicle automation, including Adaptive Cruise Control and Active Steering.  

- **Overreliance and skill degradation**  
  Some of the earliest discussions on automation and human factors, it has been recognised that transferring a task previously under manual control to automation will affect the ability of the operator to perform the task manually in the future. This can become problematic when manual control must be resumed due to automation failures, but it also has implications for future operators, who will begin their training with the automated systems in place.

### Conclusion

This research used a range of user-centred approaches to examine the needs for assistive technology in mining. The outcomes supported the prototype technology currently being developed. The work showed that human factors researchers can work successfully with technology developers in mining, and that a detailed understanding of user requirements is beneficial.

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### References