Evaluation of the efficiency of smart underground mine evacuation through virtual reality simulations

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Underground mines are inherently dangerous due to potential hazards such as fires, explosions, and caving of rock. Although these events are rare, once they occur a speedy and safe egress of mineworkers is critical to survival. Static evacuation systems use exit signs or directional lines but can get obstructed or be hardly visible in smoky or dusty conditions. This paper presents the investigation of the effectiveness of a smart evacuation technology in underground mining, where a real-time guidance system leads individuals on an optimised path to the egress while avoiding danger zones, compared to conventional practices. Participants simulated an evacuation from a virtual reality mine, using the conventional system and the smart evacuation system with real-time guidance. The highest reduction in evacuation time using the smart method amounted to nearly 40% on average. Moreover, 83% of participants preferred the smart guidance system, and agreed that it could enhance safety.

INTRODUCTION

The excavation of rock underground carries some inherent dangers such as caving or roof collapse, which can trigger mine evacuation once they occur. Additionally, mining equipment that is needed to execute the production steps, introduces the danger of catching fire or igniting the mine gases. During a mine evacuation, every minute can be critical for the survival of the miners. The most common evacuation destinations are the main entrances/exits of the mine, such as a ramp or mine shaft, or the refuge chambers, which provide temporary safety until the mine emergency rescue team arrives and safely escorts them to the surface. A National Institute for Occupational Safety and Health (NIOSH)-funded report on escape strategies for underground coal mines concluded that: “[…] research on current mining practices and the results of changes brought about by enactment of the 2006 MINER Act are lacking.” (Alexander et al., 2010) Additionally, they found that compared to non-mining industries as well as mining practices in other countries: “[…] the US Research or technology transfer into the overall U.S. mine emergency response system has been found to be lacking […]”. Therefore, research and development of a new generation of mine evacuation technologies needs to be conducted.

In buildings, emergency plans are comprehensively established, with marked exit routes, and fire extinguishers. Researchers have developed smart evacuation guidance systems that guide the evacuee on the shortest and safest path out of the building or similar structure, even when the predefined route gets obstructed. Most of these systems make use of the Internet of Things (IoT) and utilise a number of sensors, smart evacuation indicator boards (Chen, 2009; Galea et al., 2016), or even the occupant’s smart phone as localisation and emergency guidance system (Inoue et al., 2008; Ahn and Han, 2011; Majumder et al., 2017; Lujak et al., 2017). It is also worth noting, that most authors proposed to employ wireless communication between the single evacuation system components.
In underground non-coal mines route marking is the only evacuation route guidance that is required by law (30 CFR § 57.11051 - Escape routes, 1985). A mining company can choose to install lifelines, which give tactile directional cues to the nearest exit. Those predetermined routes are static and cannot take changing conditions, such as a fire in the main hallway or main drift, into account. Although, a considerable amount of research has been conducted on smart evacuation guidance systems for highway tunnels, and occupational buildings such as in Bernardes et al., (2015); Ronchi et al., (2015); Cosma et al., (2016); Arias et al., (2019) and many others, smart evacuation has not been implemented in the mining industry yet. However, the idea of implementing smart evacuation systems in underground mines is not new. Jalali and Noroozi (2009), Barker-Read and Li (1989) and Rehman et al. (2018) have developed different smart evacuation algorithms for underground mines. In general, a smart evacuation system needs to track the presence of people throughout the mine, use the IoT to localise the danger and track the environmental conditions, compute the optimal evacuation routes, and finally navigate miners to the safe destinations. Indoor localisation and tracking of individuals can be achieved by using the Received Signal Strength Indicator of the WiFi signal, beacon technology or Radio Frequency Identification technology. In particular, beacons are relatively cheap, and therefore a more dense and hence more accurate mesh network can be installed for the same or even lower price as the other two technologies. (Lujak et al., 2017). Continuous monitoring of the environment through smoke detectors, thermometers and other sensors can be used as a medium for detecting potential hazards, and different types of wired/wireless technologies may be utilised as the communication system. In general, wireless systems are preferred due to being resilient to the harsh conditions of mining, in terms of installation and maintenance of the system. Additionally, wireless mesh networks still function when one node, which functions as a wireless router, gets damaged or stops working. In this case signals will simply be rerouted to other nodes (Carrier, 2018; Strickland, 2008). Finally, diverse methodologies such as smart exit signs with changeable direction indicator or smartphones/watches are used for navigating the people. For the latter, localisation and navigation can be customised for each occupant individually. Brenkley et al., (1999) have criticised the sole use of reflective signs and symbols. According to them, the disadvantages lie in the maintenance of the signs, such as cleaning and updating, the little attention paid to them by mineworkers, and the limited visibility in adverse conditions. Furthermore, the visibility of exit route signs can be considerably decreased in low-visibility conditions (Martell et al., 2019). Chen et al., (2018) and Jeon et al., (2011) have found that low visibility conditions, such as caused by smoke, increase evacuation time.

Since other industries have successfully developed real-time, personalised evacuation guidance systems, it can be claimed that the safety in mining could benefit immensely from such approaches, in order to avoid loss of orientation or inhibit the adverse influence of bias on the decision-making process. The NIOSH currently funds a research project to develop a smart evacuation technology based on beacons, evacuation optimisation, and smartwatch navigation. This paper examines the effectiveness of a smart underground mine evacuation technology and quantifies the differences in comparison to the traditional practices as more elaborately explained in Gaab (2019). In this paper, virtual reality (VR) technology is used to simulate an underground mine evacuation. Virtual environment (VE) is utilised to study evacuation performance among the participants who were positioned in the VR world and asked to find a point of egress within the VR mine.

MATERIALS AND METHODS

Problem Statement
Current evacuation guidance systems in underground mining can show major limitations in low-visibility conditions or changing environmental conditions. Guidance and orientation systems are expected to decrease evacuation time, be visible in very adverse conditions, provide unambiguous, and if possible a combination of visual, audible and tactile clues, pose low costs and maintenance, allow for flexibility to accommodate frequent changes in the mine’s layout, be fail-proof and not reliant on background lighting. (Brenkley et al., 1999) In this paper, we study whether a novel evacuation guidance approach could save crucial time during underground mine evacuations.
Experimental Setup
For rendering the VE an HTC Vive Head-mounted display is utilised and a Virtuix Omni treadmill for locomotion as can be seen in Figure 1. Once the user puts on the Omni overshoes with attached tracking sensors, he/she can step into the Omni treadmill and start walking. Through the concave design of the Omni base and the low-friction shoes, the feet of the user will glide back to the centre after every stride. The user can, therefore, walk in place and move more naturally than other conventional VR locomotion mechanisms, such as teleportation or flying. As actual movement in the desired direction helps people navigate through a three-dimensional world, the Virtuix Omni treadmill was selected as it provides participants with the necessary idiothetic (self-motion) cues. (Jansen-Osmann and Fuchs, 2006; Sharma et al., 2017; Mallot et al., 1998, Chance et al., 1998).

A user interface(UI) is created, which always stays in a predefined position in the user’s field of view (FOV). The UI is used to transmit information to the user inside the game, such as the time of playing and instructions. Then smoke is added in the VE to make the dangers more evident to the participant. The smart navigation waypointer moves with the rotation and movement of the camera, and thus the user’s head, and will always turn in the direction of the shortest path to the egress point. The layout of the two different evacuation wayfinding systems is depicted in Figure 2.

Figure 1. VR set-up using the HTC Vive (HTC Corporation, 2019) and the Virtuix Omni treadmill (Virtuix, 2019).

Figure 2. a) Conventional method: Example of egress route sign placed on a drift wall; b) Smart method: smart wayfinder floating in front of the user and turning its tip toward the nearest exit
In all simulations, the user is equipped with a virtual headlamp, that moves and rotates with the head and therefore with the view of the user as well. In the illuminated conditions, light sources were added to the drifts and in the dark conditions the headlamp is the only light source, which decreases the FOV largely (compare Figure 3).

![Figure 3. a) Illuminated condition, b) Dark condition with restricted FOV.](image)

**Experimental Design and Evacuation Scenarios**

To assess the efficiency of each evacuation method, a special process is constructed within-subject design for the experiments. In order to eliminate a learning curve when participants are transitioned from the conventional to the smart method, the participants first entered an introductory level where they were able to experience and get used to the Head Mounted Display (HMD), locomotion, haptics, and controls used in the simulation and the VE until they claimed to feel “comfortable” using those.

Once the participant starts the simulation, he/she is directed through signs only (conventional) or a wayfinder (smart) to a first evacuation target. However, as soon as they reach the first target, they are redirected to a second evacuation target as the first one will prove to be unusable during the simulation, the user is told via the interface to redirect. Upon the start of each simulation, a timer started and recorded the variable ‘total time’, to evaluate how long it takes to go from the starting point to reach the final (second) target. Additionally, a pre- and post-survey collected information about prior experiences with VR and underground mines as well as personal preferences, and the experience with the VR during the simulation. Statistical analysis is conducted to determine if the smart evacuation method is more efficient than the conventional approach and if so, how much time could be saved by implementing a smart guidance system. The anticipated benefits of a smart evacuation method in comparison to the conventional methods is tested through two corresponding hypotheses: (i) Smart evacuation is faster, (ii) Smart evacuation leads to more confident decision making.

Figure 4 shows the order of simulations. The illuminated simulations (indicated by the capital letter ‘I’), take place on the same mine level, as well as both simulations in dark conditions (indicated by capital letter ‘D’). The difference between the illuminated and dark conditions is that the FOV of the user is considerably smaller in the dark conditions (refer to Figure 4). In addition, they cannot see down the drift/path as much as in the illuminated simulations. The same levels were chosen in order to ensure that the same complexity was met in the conventional (indicated by the capital letter ‘C’) as well as the smart method (indicated by the capital letter ‘S’). The complexity is defined as the number of possible directions taken along the shortest route, and number of intersections. Both evacuation routes in the conventional and smart method were different. However, to make them comparable, all metrics such as distance to the final target, number of curves, number of obstacles, obstacle occurrence time and distance of obstacles were the same. The experiment was concluded with a post-survey that assessed the sense of presence according to the Presence-Questionnaire by Witmer and Singer (1998).
RESULTS

Sample Description
In total, 13 participants voluntarily conducted the simulations. Three people did not walk through all simulations, as they had developed fatigue or motion sickness in the simulations before, and therefore did not feel comfortable proceeding. One person did not successfully finish the conventional, dark simulation as the person got lost in the mine for over ten minutes, and asked to stop.

Quantitative Data
In Figure 5 the average evacuation time of all simulations CI (N=13, $\bar{x}$=328.46, $\sigma$=103.58), SI (N=13, $\bar{x}$=198.23, $\sigma$=47.41), CD (N=9, $\bar{x}$=220.89, $\sigma$=52.36) and SD (N=9, $\bar{x}$=183.56, $\sigma$=49.76) are compared. As can be seen in this Figure, the average time to evacuate using smart evacuation (SI, SD) was in all cases lower than the time needed when using the conventional method (CI, CD). However, it is notable that the participants on average finished the simulation in CD and SD sooner than in the CI and SI. Noteworthy is the performance difference between CI and CD. Even though the participants’ FOV was limited in CD they outperformed the average time compared to the one in CI by 32.75%.

The variability for the collected data in all four simulations is visualised in Figure 7. For CI, the standard deviation ($\sigma$=103.58) is strikingly higher than for SI ($\sigma$=47.41), CD ($\sigma$=52.36) and SD ($\sigma$=49.76). This makes it evident that the total times in CD were partially far spread around the mean, with a maximum time of 521 seconds, and a minimum time of 178 seconds. Even though the value of 521 in dataset CI looks like it could be an outlier, a closer look at the acceptable data range that is defined by two standard deviations from the mean and results in (121.30, 535.62) confirms that all data in CI is within the range. The time it took to evacuate in CD is not as consistent as in all other simulations SI, CD, and SD. The difference between the standard deviation of SI, CD, and SD is not considerably high. To conclude, if the difference between the simulations was significant, a matched pair t-Test was conducted, comparing each method to one another, and are given in Table 1.
Figure 5. a) Average time needed to finish each simulation and range of error b) The variability (σ) (box), collected data points (dots) and maximum and minimum values (whiskers) as well as the mean (x̄) (line) of the total times collected for each simulation.

Table 1. Statistical significance of the difference between the total times of the methods as well as the achieved reduction in total time

<table>
<thead>
<tr>
<th>Time Difference (d) (x1 &gt; x2)</th>
<th>Average time reduction</th>
<th>p-Value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI - SI</td>
<td>-39.65 %</td>
<td>0.000554</td>
<td>significant</td>
</tr>
<tr>
<td>CD - SD</td>
<td>-16.90 %</td>
<td>0.021974</td>
<td>significant</td>
</tr>
<tr>
<td>CI - CD</td>
<td>-32.75 %</td>
<td>0.018969</td>
<td>significant</td>
</tr>
<tr>
<td>SI - SD</td>
<td>-7.4 %</td>
<td>0.037993</td>
<td>significant</td>
</tr>
</tbody>
</table>

Each probability value (p-Value) that is lower than the previously defined significance level α = 0.05, indicates that there is a significant difference between the data sets of the compared simulations. In all cases, there was a significant difference in total time. The smart evacuation was in all cases significantly faster than conventional evacuation. Evacuations in the dark environment were significantly faster than in the illuminated environment. The biggest average time reduction can be observed between CI and SI with a percentage of -39.65%. Another considerable difference can be observed between CI and CD where time was reduced by 32.75%, thus evacuees were faster in the dark environment. Between CD and SD, a p-Value of 0.015036 indicates a significant difference, meaning that the simulations in SD went considerably faster, and reduced the average total time by 16.90%. When comparing SI against SD the p-Value of 0.037993 is on the verge of being statistically significant. A time reduction of 7.4% was observed.

Qualitative Data
Figure 6 gives a visual representation of how often the participants were turning in the Omni for CI and SI, either changing their walking direction or turning to look around. Comparing the amount, and even density of vertical lines in both graphs, it is concluded that participants turned around more while using the conventional evacuation method. This could indicate that some participants did not find the shortest route, had to redirect, or ensure that they had chosen the right path, whereas in the smart evacuation method participants mostly followed the arrow. The homogeneity in reoccurring turning patterns for
each participant in SI can be interpreted as a lower level of confusion about where to go, as most participants took similar turns at similar times. At this point, it should be reinforced that both levels had the same amount of 90° and 180° turns. Looking at the same graphs for CD and SD, no considerable difference can be visually noticed between the amount and sequence of turning using the conventional method or smart method.

Figure 6. Angle of turning in the Omni during CI and SI, the turning sequence of each participant is indicated by the participants’ number and the dotted, vertical lines.

The post-survey gave qualitative information about the feeling of presence within the VE, and the personal preferences of the participant. Furthermore, it was investigated whether participants felt if the apparatus influenced their performance considerably. It was concluded from this survey that most participants felt rather immersed than disconnected from the VE, and that the locomotion technique through the treadmill did not interfere with their performance of the assigned task. One person noted that it was very interesting, and felt real, while another person stated that the “shaking of [the] virtual world”, which can be assumed to refer to a low frame rate, caused motion sickness.

In total, 83% of the participants claimed that they preferred the smart evacuation over the conventional method, with some comments like (i) “[...]it’ll guide me to where I need to go without me worrying about not taking the right turn”, or (ii) “[smart evacuation is] easier to follow, less thinking”. In addition, 100% of the participants thought that smart evacuation can contribute to safety in mining, with statements given such as (i) “Definitely much better [than signs] even if there were more signs”, (ii) “[...] can definitely help me to consume a lower amount of energy” [...], (iii) “Yes, because it would help me save time and get to safety faster”, (iv) “[...] people will be calm”, and (v) “Yes, I do think it would contribute immensely”.

Two participants commented that there should be more signs throughout the mine, with one person stating that he thinks the smart evacuation would still be “superior” to the conventional method.
CONCLUSION
Overall, the study confirms the initial hypothesis stating that smart evacuation is more efficient than the conventional method, and leads to more confident decision-making. The maximum time reduction achieved by using the smart evacuation instead of the conventional evacuation method amounts to up to 40%. In total 83% of the participants preferred the smart evacuation method over the conventional evacuation method, and 100% seconded that smart evacuation could be beneficial for miners’ safety during mine evacuations. Results recommended recruiting a larger number of volunteers, and conducting experiments based on a between-subjects design rather than a within-design. This prevents the occurrence of a learning effect which can influence the results negatively. Moreover, a between-subjects design reduces bias or possible disadvantages or advantages that can unintentionally occur due to different but random route assignments.

Furthermore, when taking the post-survey answers, the frequency of turning in the VR world, as well as video and screenshot footage into considerations, it was indicated that the participants felt more confident in their decision-making process when they followed the smart wayfinder. They preferred the “easy” guidance and had to turn around less to evaluate which way would bring them to the safe area faster.

Even though it was attempted to prevent a major learning effect throughout the simulation with the use of an introductory level, a minor learning effect cannot be eliminated. Against the authors’ expectations, the participants did not perform worse, but in most cases even better in the dark simulation environment where their FOV was constrained to a small angle, and their visibility range shortened. This was perceived to be caused by a slight learning curve during the simulations, as participants had acclimatised to the use of the treadmill and the wayfinder.

In this study, only one isolated aspect of the smart evacuation was looked at, which is the real-time guidance. We believe that an investigation on how smart evacuation can outperform conventional methods when registering hazardous conditions beforehand, and guiding the evacuees on an optimal route from the very beginning would be necessary. In this study, an inherent advantage was not given to the smart evacuation method by leading the participant straight to the final target, instead of running into one obstacle first. When implemented in an actual mine, the smart guidance systems should detect the obstacle or hazard condition, and compute the shortest and safest route based on this information. Another feature that could be implemented is an algorithm that takes the individual’s fitness into account. This could help to distribute miners among refuge chambers and shafts based on a way that, for example, less fit miners would have to walk less and would have a higher chance of reaching a safe area in time. Moreover, if this algorithm is fed with the maximum occupancy of the refuge chambers it could ensure that none of the chambers get overfilled.

Once the efficacy, reliability, and algorithms of a smart evacuation guidance system have been further proved and improved, a study should be conducted to determine what device is best suited for the smart wayfinder.

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