Virtual Environment for Studying the Effects of Operational and Environmental Sounds on Teleoperated Demolition

Patrick B. Rodrigues[1]; Burcin Becerik-Gerber, Ph.D.[2];
Lucio Soibelman, Ph.D., P.Eng., Dist.M.ASCE[3]; Gale M. Lucas, Ph.D.[4];
and Shawn C. Roll, Ph.D.[5]

[1]Sonny Astani Dept. of Civil and Environmental Engineering, Viterbi School of Engineering, Univ. of Southern California, Los Angeles, CA (corresponding author).
Email: borgesro@usc.edu
[2]Sonny Astani Dept. of Civil and Environmental Engineering, Viterbi School of Engineering, Univ. of Southern California, Los Angeles, CA. Email: becerik@usc.edu
[3]Sonny Astani Dept. of Civil and Environmental Engineering, Viterbi School of Engineering, Univ. of Southern California, Los Angeles, CA. Email: soibelman@usc.edu
[4]USC Institute for Creative Technologies, Univ. of Southern California, Los Angeles, CA.
Email: lucas@ict.usc.edu
[5]Chan Division of Occupational Science and Occupational Therapy, Univ. of Southern California, Los Angeles, CA. Email: sroll@chan.usc.edu

ABSTRACT

Teleoperated robots are increasingly being used in construction sites, but there is still a need for better human-robot interfaces. Auditory feedback using sonification has commonly been used to complement visual feedback in teleoperation applications. However, it is not yet well understood how operational and environmental sounds can support operators in complex tasks such as construction machine operations. In this paper, we describe the development of a virtual environment to assess the impacts of operational and environmental sounds on operators' performances and cognitive loads during teleoperated demolition. Our goal is to examine whether different levels of operational and environmental sounds can increase the workers' situation awareness, operational efficiency, and safety performance. Alternatively, we anticipate that some environmental noises may negatively affect the operators' performances by increasing their mental workload and stress levels. Consequently, we plan to evaluate the effectiveness of including audio filters that minimize unwanted sounds while prioritizing desired sounds.

Keywords. Auditory feedback, demolition, human-robot interfaces, operators' performance, teleoperation.

INTRODUCTION

The construction industry is experiencing a significant increase in the number of robots deployed on- and off-site. In most cases, these robots are not entirely autonomous and require different degrees of operator assistance depending on the task, the robot, and the user interface. As a result, remotely operated and teleoperated robots (i.e., operated within the operator's field of view or through a screen, respectively) are the most common types of robots used in construction sites. Specifically, for teleoperated robots, although many safety benefits have been associated with their usage, operational performance-related challenges remain. Among them, reduced situation awareness, productivity, and increased mental workload have been identified because of the physical separation between the operator and the task site (Rea and Seo 2022).

One potential benefit of teleoperation in construction is related to the reduced exposure of operators to environmental noise. The construction industry is among the industry sectors with the highest levels of occupational noise exposure, with 51% of the workers reporting being exposed to hazardous noise conditions in their worksites (Kerns et al. 2018). Although the risk of incident hearing loss among construction workers has decreased since the 1980s due to safety regulations, the construction industry still has one of the highest prevalence and incidence rates of workers' hearing loss among all industry sectors (Masterson et al. 2015).

Not only is environmental noise associated with hearing loss and other health problems such as heart disease and insomnia, but it can also affect the operators' cognitive performance and attention levels (Ke et al. 2021). For example, environmental noise can affect robot operators' task performances and increase task completion times, and total distance traveled for the robot's end effectors, especially in more complex tasks (Siu et al. 2010). Also, environmental noise associated with construction tasks has been shown to affect the physiological response (i.e., heart rate, respiratory rate, and electrodermal activity) of people exposed to these noises, which varies depending on noise types and exposure duration (Mir et al. 2023).

In teleoperation applications, as the auditory feedback from the site is provided through speakers or headphones, the operators have more control over the sound levels they experience during the task. In many applications, however, auditory feedback is not provided or only provided as non-speech sounds (e.g., alarms, beeps) that indicate potential collisions or hazards. There is, however, a potential that including some operational and environmental sounds in teleoperation interfaces for construction machines may increase the workers' situation awareness and, consequently, their operational and safety performances. In this study, we describe the development of a virtual environment designed to study the impacts of providing operational and environmental sounds to construction robot operators in teleoperation applications. Specifically, we focus on understanding the effects of operational and environmental sound on the operators' psychophysiological responses and operational and safety performances. The virtual environment aims to replicate a teleoperation interface for a demolition robot being used to demolish concrete elements in a multistory building.

RELATED WORK

One of the main issues associated with using teleoperated robots is the decoupling between the operators' natural perception processing and the physical environment because the operator is removed from the job site (Fu et al. 2015). This decoupling can affect the operators' performance and their sense of telepresence (i.e., the feeling of being present at the site) and agency (i.e., the feeling that they cause the motions of an object), for example. Existing research shows that including auditory feedback in teleoperation interfaces can overcome this issue to some extent and increase the operators' sense of presence, task performance, and engagement (Khenak et al. 2018) and sense of agency (Morita et al. 2022).

The inclusion of auditory feedback in teleoperation workstations can also benefit the users' operational and safety performances. Relative to operational performance, existing studies show that auditory feedback increased the operators' spatial positioning performance and accuracy in manipulation tasks (Triantafyllidis et al. 2020). Also, voice and ping signals in teleoperation workstations have been associated with increased accuracy in spacecraft proximity operations

(Harder et al. 2016). Relative to the impact of auditory feedback on the user's safety performance, existing studies show evidence of improved hazard recognition performance and safer behavior during task execution after the inclusion of background sound in the user interface (Lu and Davis 2018; 2016). Including auditory feedback in the user interface has also been shown to reduce operators' levels of mental workload (Bremner, Mitchell, and McIntosh 2022). Finally, including auditory feedback may also be associated with reduced distractions and increased task engagement as it masks sounds from the environment where the operator is located (Lu and Davis 2018; 2016).

Despite these results, it is not always the case that including auditory feedback necessarily leads to improved operational and safety performances. Many of the studies presented in this section did not find significant differences in the users' sense of telepresence or operational and safety performances after the inclusion of auditory feedback (e.g., Bremner, Mitchell, and McIntosh 2022; Harder et al. 2016; Morita et al. 2022). In other cases, the study could not find evidence that the inclusion of auditory feedback affected the users' perceived levels of mental workload or usability of the interface or the number of errors and completion times associated with the task (Triantafyllidis et al. 2020). In more extreme cases, the inclusion of auditory feedback even led to operators' discomfort, as perceived by the users trying to turn down the headphones' volume or remove them when exposed to sounds around 85 dBA (Lu and Davis 2016).

The common practice in teleoperation interfaces that include auditory feedback is to use sonification, i.e., non-speech acoustic signals that convey information about the task or the environment. These signals may be used to indicate the speeds of the robot's movements (e.g., Morita et al. 2022), warnings, notifications, and interactions of the manipulated objects with the environment (e.g., Triantafyllidis et al. 2020), and the risks associated with radiation, collisions, and overloading the robot (e.g., Bremner, Mitchell, and McIntosh 2022). It is also usually the case that these applications are based on virtual reality or simulations, in which cases the designers of the virtual environment can control the types of elements interacting with the robot. However, accounting for all elements that can interfere with the task and potentially create problems during teleoperation can be a more complex issue for real construction sites where unstructured and dynamic conditions occur.

In construction applications, there is a potential that operational and environmental sounds can provide key operational and safety information that can increase the users' situation awareness and, consequently, their operational and safety performances. Among the few studies in the construction industry that used actual construction audio clips to study the impacts of their inclusion on the user's safety performance, Lu and Davis (2018; 2016) studied the implications of salient and background sounds on the users' hazard recognition performances. These studies, however, were not sufficiently powered and failed to identify some significant effects.

METHODS

Task Description. The selected task for the virtual environment was the demolition of concrete walls and slabs in one room of a four-story building. This was intended to allow the users to experience the demolition of vertical and horizontal elements using the breaker. In the simulations, the users were provided with information about the elements that required demolition, but they had the freedom to determine the sequence of operations.

Robot Description. The Brokk 110 demolition robot (Figure 1 (a)) was selected for the virtual environment described in this paper. This machine is a compact, remotely operated demolition robot. The robot was originally designed to be remotely operated, which is done through its SmartRemote™, with the operators located on-site and the robot located within their fields of view. In the virtual environment, the robot was adapted to be teleoperated through a computer screen (Figure 1 (b)). Five cameras and a microphone were attached to the simulated robot's body in locations that mimic potential locations for these sensors in the actual robot. Although the manufacturer provides a variety of end-effectors for the robot, only the breaker was included in the virtual environment to simplify the training and subsequent experimental sessions.

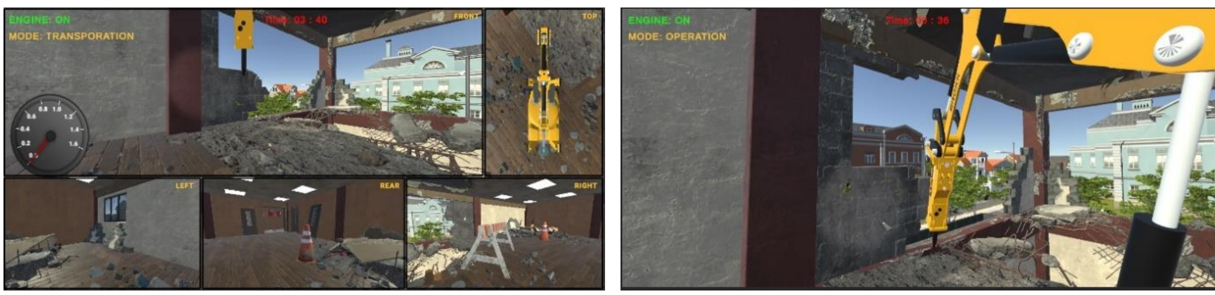
(a) (b)

Figure 1. (a) Remotely operated Brokk 110 and (b) teleoperated Brokk 110 (3D model).

Proposed Workstation. The proposed workstation (Figure 2) consisted of an Intel® Core™ i7-11800H @ 2.30 GHz, 32 GB RAM laptop with an NVIDIA GeForce RTX 3080 Laptop GPU 16GB GDDR6, a 27 inches computer monitor, two ambidextrous joysticks (model Thrustmaster T.16000M Space Sim Duo Stick), and an immersive cinematic 3D audio headset (model Audeze Mobius Spatial Audio Gaming Headset). The laptop and screen were mounted on an electric height-adjustable desk, and the joysticks were attached to the arms of an ergonomic office chair.

Figure 2. Proposed teleoperation workstation.

Virtual Environment Features. The virtual environment was developed using the Unity game engine. All possible motions of the actual robot were reproduced in the simulated robot, including turning the engine on/off, driving and turning the robot, moving the outriggers, slew system, arm system, and breaker, and activating the breaker. In the virtual environment, the operators were able to regulate the robot's speeds through the joysticks' movements. The robot was represented by a physical object interacting with other objects in the scenes. It was also subject to the effects of gravitational forces, which could lead the robot to fall if it moved over a hole in the floor or an edge of the building. In the proposed teleoperation interface, the robot could be in two modes: transportation and operation. In the transportation mode (Figure 3 (a)), which was used to drive the robot and control its outriggers, the users were provided with views from the five cameras installed in the robot (i.e., front, rear, left, right, and bird's eye). Alternatively, in the operation mode (Figure 3 (b)), which was used to control the robot's arms, the users were provided with one camera that followed the breaker as it moved.



(a) (b)

Figure 3. (a) Transportation mode and (b) operation mode interfaces.

The demolition behaviors of the elements in the scenes were simulated using the Rayfire plugin, a plugin commonly used by movie and video game studios to create visual effects. As a result, during the demolition tasks, individual pieces of the concrete walls, slabs, columns, and beams dynamically reacted to the forces applied by the breaker. When these forces overcame the damage threshold for each piece of concrete, the piece was detached from the structural element and was affected by gravitational forces and interactions with other objects in the scenes. These pieces also interacted with the rebar in the structural elements in the virtual environment.

The virtual environment included sound effects that emulated the sounds of the robot and the environment. These sounds were mapped to each component of the robot, workers, other construction equipment and tools present in the scenes, traffic, and collapsing elements. Using an immersive 3D audio headphone allowed the users to localize the sound sources in the virtual environment, which could be used to increase the operators' situational awareness (e.g., hearing collapsing elements or approaching workers). As mentioned, a microphone was attached to the simulated robot so the operator could perceive the distance and location of the sound sources relative to this microphone.

Operations and Safety Training: To help the virtual environment users get familiar with the control and safety mechanisms of the robot, a training module was included in the virtual environment. During the operations training (Figure 4 (a)), the users learned how to turn the robot on/off, drive it, position its outriggers and arms, and use the breaker. During the safety training (Figure 4 (b)), the users learned about the safe operation of the robot, which included avoiding collisions, avoiding flipping the robot or falling through holes or over the edges of the buildings, and reacting to collapsing elements and workers/objects entering the demolition areas.

Virtual Environment Sound Conditions. The virtual environment included three different sound conditions: *no sound, full sound, and filtered sound*. In the *no sound* condition, the users did not receive any auditory feedback throughout the simulations. This condition replicated the current state of many existing teleoperation interfaces used in construction that do not provide auditory feedback from the site to the operators. In the *full sound* condition, the sounds from the robot, other equipment, workers, and traffic, among others, were provided to the users. Differences in the sound levels from different objects were a function of the reported sound levels for these objects in the literature and the relative distances between these objects and the microphone installed in the robot. This condition replicated existing teleoperated interfaces that provide auditory feedback from the site to the operators through microphones installed on the robot or on-site. Finally, in the *filtered sound* condition, the users received the same types of sounds as in the *full sound* condition; however, the robot's operational sounds and uninteresting environmental noise, such as traffic, were filtered to reduce their sound levels. Thus, the *filtered sound* condition prioritized sounds that indicated approaching equipment, workers, and collapsing elements. Operational sounds from the robot, which indicated the operating conditions of the robot, were reduced but not eliminated. This condition simulated a proposed teleoperation interface in which certain sound types were prioritized to potentially increase the operator's situation awareness and hazard recognition ability.

(a) **(b)**

Figure 4. (a) Operation training and (b) safety training.

For both the *full sound* and *filtered sound* conditions, sound effects collected from real construction sites were mapped to each element in the scenes. For example, for every movement of the robot's components, an audio source was played whenever the component was used. Audio sources were also linked to other objects in the scenes, such as construction equipment and tools, workers, and traffic. In the virtual environment, various audio mixers were used to mix and output the audio sources and to adjust the sound levels from each source. Audio effects (e.g., attenuation) were added to modify the audio mixers. The Unity Audio Spatializer SDK was used in the virtual environment to support audio spatialization. The perception of the spatial audio features was done through the 3D audio headset, which uses a direct Head-Related Transfer Function (HRTF) that the Unity Audio Spatializer SDK supports. Figure 5 presents a schematic representation of the audio features of the virtual environment.

Measures of Interest. As presented, the virtual environment was designed to serve as a testing ground in studies that aim to assess the impacts of operational and environmental sounds on the operators' psychophysiological responses and operational and safety performances. Among the psychophysiological measures of interest, electrodermal activity and heart rate were used to indicate cognitive load and stress. Operational performance metrics included productivity, time to complete the task, and the number of collisions between the robot and other objects. Safety performance metrics included safety behaviors during operations and the reaction times after accidental collapses or workers entering the demolition areas.

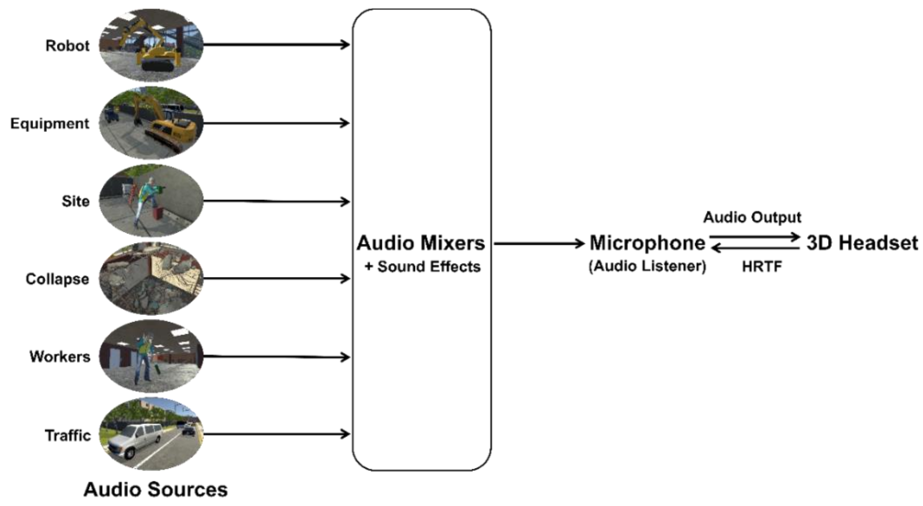


Figure 5. Schematic representation of the audio features of the virtual environment.

Except for the psychophysiological measures, all other measures were directly implemented in the virtual environment. For performance metrics such as time to complete, productivity, number of collisions, and reaction times, scripts generated a report at the end of each session. The movement of the joysticks on the x-y axes and the speeds of the robot and its arms were collected as time series data. Finally, subjective assessments were also included in the virtual environment. Situation awareness was assessed using the Situation Awareness Global Assessment Technique (SAGAT), workload was assessed using the NASA Task Load Index (NASA-TLX), and anxiety was assessed using the 6-item Spielberger State-Trait Anxiety Inventory (STAI).

CONCLUSIONS AND FUTURE WORK

In this paper, we described the development of a virtual environment for teleoperated demolition robots to be used to study the effects of operational and environmental sound on the operators' psychophysiological response and operational and safety performances. Future research efforts involve testing the virtual environment with an appropriate sample size and validating the study results using the interface being developed for the actual teleoperated demolition robot.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation under Grant No. 2222572 and the U.S. Army Research Office under Grant No. W911NF-20-2-0053. Any opinion, content, or information presented does not necessarily reflect the positions or the policies of the National Science Foundation's or the U.S. Army Research Office's views, and no official endorsement should be inferred.

REFERENCES

Bremner, P., Mitchell, T. J., and McIntosh, V. (2022). "The impact of data sonification in virtual reality robot teleoperation." *Front. Virtual Real.*, 3:904720.

Davila Delgado, J. M., Oyedele, L., Demian, P., and Beach, T. (2020). "A research agenda for augmented and virtual reality in architecture, engineering and construction." *Adv. Eng. Inform.*, 45:101122.
Fu, Y., Chen, W., Li, S., and Jiao, Z. (2015). "Evaluating Operator Performance in Teleoperated Manipulator System Factored by Camera Configurations." *Engineering Psychology and Cognitive Ergonomics*, Springer International Publishing, Cham, 327–334.
Harder, J., Wilde, M., Ventura, J., and Dziura, M. (2016). "Acoustic telepresence for spacecraft proximity operations." *2016 IEEE Aerospace Conference*. IEEE, 2016:4587-12.
Ke, J., Zhang, M., Luo, X., and Chen, J. (2021). "Monitoring distraction of construction workers caused by noise using a wearable Electroencephalography (EEG) device." *Autom. Constr.*,, 125:103598.
Kerns, E., Masterson, E. A., Themann, C. L., and Calvert, G. M. (2018). "Cardiovascular conditions, hearing difficulty, and occupational noise exposure within U.S. industries and occupations." *Am. J. Ind. Med.*, 61(6), 477-491.
Khenak, N., Vézien, J., Théry, D., and Bourdot, P. (2018). "Spatial Presence in Real and Remote Immersive Environments and the Effect of Multisensory Stimulation." *Presence: Teleoperators and Virtual Environments*,, 27(3), 287-308.
Lee, H. J., and Brell-Cokcan, S. (2021). "Cartesian coordinate control for teleoperated construction machines." *Construction Robotics*,, 5, 1–11.
Lu, X., and Davis, S. (2018). "Priming effects on safety decisions in a virtual construction simulator." *Eng. Constr. Archit. Manag.*,, 25(2), 273-294.
Lu, X., and Davis, S. (2016). "How sounds influence user safety decisions in a virtual construction simulator." *Saf. Sci.*,, 86:184-194.
Masterson, E. A., Deddens, J. A., Themann, C. L., Bertke, S., and Calvert, G. M. (2015). "Trends in worker hearing loss by industry sector, 1981-2010". *Am. J. Ind. Med.*, 58(4), 392-401.
Mir, M., Nasirzadeh, F., Bereznicki, H., Enticott, P., Lee, S., and Mills, A. (2023). "Construction noise effects on human health: Evidence from physiological measures." *Sustain. Cities Soc.*, 91:104470.
Morita, T., Zhu, Y., Aoyama, T., Takeuchi, M., Yamamoto, K., and Hasegawa, Y. (2022). "Auditory Feedback for Enhanced Sense of Agency in Shared Control." *Sensors*,, 22:9779.
Rea, D. J., and Seo, S. H. (2022). "Still Not Solved: A Call for Renewed Focus on User-Centered Teleoperation Interfaces." *Front. Robot. AI*,, 9, 704225.
Siu, K. C., Suh, I. H., Mukherjee, M., Oleynikov, D., and Stergiou, N. (2010). "The impact of environmental noise on robot-assisted laparoscopic surgical performance." *Surgery*, 147(1), 107-113.
Triantafyllidis, E., Mcgreavy, C., Gu, J., and Li, Z. (2020). "Study of Multimodal Interfaces and the Improvements on Teleoperation." *IEEE Access*, vol. 8, 78213-78227.