# Virtual Reality Application for Enhancing Risk Assessment Skills

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## ABSTRACT

Conducting risk assessment on systems require a deep understanding of all aspects of the system. When training novices to conduct risk assessments, they need to form a strong understanding of the system, its relationship to the environment, and how it operates. The term mental model is used to describe this understanding. Novices, who are provided system design in a 2D format, may struggle to form a mental model for the system and, thus, may fail to embrace risk assessment processes.

Training novices can, therefore, be a significant challenge. This paper presents a 3D, full-scale, highly interactive VR application titled Collaborative-VR (CVR) that was created with the hope it will allow novices to form a high level metal model for the system. Since risk assessments are done in teams, CVR was created to allow multiple users to work in the virtual reality environment and build systems with the hope that this experience will create the desired shared mental model that they need to effectively conduct risk assessments on system.

CVR was implemented in a Risk Assessment course at Iowa State University. Students worked in teams in a full scale, virtual reality model of the International Space Station, where they were required to design a system to solve a problem and conduct risk assessment techniques on the system based on the life cycle of the project.

Observations from a pilot study that indicated that students struggled forming robust representation of the systems and, subsequently, gained limited success in assessing systems risks. These observations and understanding CVR limitations will assist in further design features of CVR to overcome these limitations; further assessment of the capability of CVR to serve for forming strong, team shared mental models, will follow the implementations of the proposed improvements.

## ABOUT THE AUTHORS

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## INTRODUCTION

Risk analysis is a common practice to ensure the safety and longevity of systems. Government and commercial entities have applied risk analysis to a variety of complex engineering projects including oil pipelines, power plants, and aerospace vehicles. Multiple risk assessment techniques exist; these techniques can be applied to various phases of a system's development. Preliminary Hazard Analysis, for example, is mainly used in the concept exploration phase where detailed designs are not available. Techniques, such as Failure, Mode, and Effect Analysis, and Fault Tree Analysis, require detailed design for performing risk assessment. These techniques are time and resource demanding; significant design flaws incur not only the cost of a redesign, but also the cost of redoing the risk assessment. Therefore, flaws in system design that are realized later in the fabrication on operation phases are highly undesired and expensive to fix.

System designs are most commonly presented in a 2D mode. Any applications that utilize 3D capabilities are usually hard to modify and limited to visualizing a 3D presentation on a 2D screen. Learning to understand a system design from a 2D drawing is somewhat of an art, which may take years to develop skills for. Thus, training for hazard recognition and the corresponding risk, specifically for novices, can become a challenge. The question may arise are whether, (1) development or review of systems in a full-scale, 3D, interactive environment such as virtual reality (VR) will provide a venue for training novices in risk assessment, and (2) since risk assessments are usually conducted in teams, if it is possible to develop a VR system where teams can collaborate.

To address the first question, unlike traditional risk assessments, VR offers a more accurate sense of scale and view the industrial system design using multiple orientations, which help designers discover more design flaws (Li et al., 2004; Puschmann et al., 2016). Puschmann et al. (2016) developed a general framework for designing VR risk analysis scenes and found that certain risks are more exposed at certain viewpoints of the industrial system design. Puschmann et al. (2016) also found that more complex designs reveal more design flaws than simpler designs. When combined with real-time dynamic simulations, VR can also effectively train users to understand different operations and equipment without endangering the user, allowing endless experimentation on industrial system designs and training solutions (Nasios, 2002). Wyk et al. (2009) developed four VR training solutions to train future workers to identify hazards, view causes of accidents, understand the correct procedures to prevent accidents, and understand restricted field of vision and controls when operating vehicles in the mining industry. Wyk and colleagues found that the trainees were engaged in the VR simulations and the hazards and the mining environment were realistic enough to prepare the workers for risk prone operations.

Prior to answering the remaining questions, VR systems should be described. VR is a visualization tool. Systems facilitating VR can range from CAVE™ (Cruz-Neira et al., 1993) to Head Mounted Devices (HMD). Figures 1a and 1b present a CAVE based system and an HMD system, respectively. In CAVE systems, multiple agents can be physically present in the VRE and collaborate while reviewing systems rendered in 3D. However, CAVE™ systems are expensive to build/buy and operate and require multiple computers to create the VRE. In recent years, however, the increased desktop and laptop computational and graphic power and advent of higher capability HMDs open new horizons.

**Figure 1a. C6, a CAVE<sup>TM</sup> based system at ISU**



**Figure 1b. HMD-based system**

A desktop with a powerful graphics card and an HMD, such as HTC Vive or Oculus Rift, can provide stunning visual equity while delivering dynamic simulations with complicated graphic user interfaces. These developments changed the landscape of the virtual reality arena.

The general premise in the efforts reported herein is that physically building a system can improve retention of risk assessment in novices. When training for assessing risks, the ability to actually build a system from components and manipulate these components to adjust system design to address hazards and risk enhances the imprint of assessment processes in trainees' cognition by developing robust mental model for the system through the process. Don Norman (2013) writes:

> *People create mental models of themselves, others, the environment, and the things with which they interact. These are conceptual models formed through experience, training, and instruction. These models serve as guides to help achieve our goals and in understanding the world*. (P. 31)

As described above, risk assessments are usually be conducted in team, and thus the shared mental model is of importance. With regard to team shared mental model (TSMM), there is a spectrum of operation that needs to be considered. On one side there is an action-oriented teams such as SWAT teams and firefighters where synchronized operations are highly reliant on other team members, and timing and recognition based on anticipation are critical to the mission (Cooke, Gorman, Duran, & Taylor, 2007). On the other side of the spectrum are team interactions that are not mission critical, and operation is decision-oriented and knowledge based (Endsley & Pearce 2001). Here patterns of cognitive similarity to retrieve shared information is at the core of the interaction and success. DeChurch and Mesmer-Magnus (2010) indicate that this side of the spectrum is more typical for software design and management team consulting. We identify the case here to belong to this group of team interactions. When taking this information in consideration for developing a VR application that is cost effective (i.e., non-CAVE-based) and allows for interacting among team members, there are several challenges that need to be addressed:

- Collaboration is less feasible in HMD-based VR because current technology only allows a single user to utilize the HMD system.
- Even if the issues associated with multiple actors in HMD-based VR are resolved, a synchronized virtual environment is required for collaboration. All required object properties must be synchronized with all connected users to successfully analyze system designs.
- Users must be able to manipulate all necessary design components in the virtual environment and synchronize all changes in real time.

- System design progress in VR should allow for saving and resuming any time on any workstation; however, it cannot be saved on servers since users need file access to resume their progress on any given VR workstation.
- Design files must also have unique filenames, which cannot be named during the VR design stage, to avoid file reading and writing conflicts.
- Finally, collaboration groups cannot interact with other groups.

**COLLABORATE-VR**

To facilitate an environment for collaborating, designing, and assessing risks in VR, we created a virtual reality application titled Collaborate-VR (CVR). Since risk assessment is broadly applied in various industries with different methodologies, CVR was created with flexible features that allow easy implementation. The overall philosophical approach in the design of CVR is that multiple users in the virtual environment will have a greater understanding of the system design and influence the system in real time. Additionally, a functioning collaborative framework can implement future features to enhance collaborative risk assessment.

**CVR Architecture**

As hinted earlier, HMDs were the chosen VR technology, since it supports head and controller tracking, allowing users to examine system designs more naturally. Since an HMD can only be worn by a single user, we utilized a server cloud from a third-party service provider and configured the client workstations to establish connections with the cloud server, without needing to setup a network server and develop a server application for collaboration. Since the server cloud is hosted in various regions, the client workstations can communicate from various locations. Taking this approach, the application can be utilized for various projects requiring to address design in public and private sectors. The application allows users to collaborate locally, regionally, and globally. The server cloud hosts vast numbers of servers and one server is randomly selected to perform collaboration with all client applications.
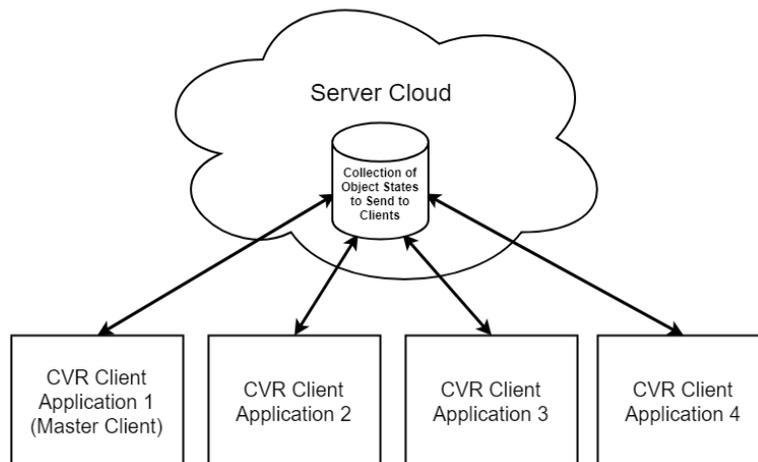


**Figure 2. Simplified overview of CVR**

In CVR system shown in Figure 2, a server in the server cloud receives an updated object state from one CVR client application and sends it to the rest of the clients to synchronize the virtual environment. The data flow is represented by bi-directional arrows, showing that the server cloud and client applications send and receive data. By continuously sending and receiving data from the server cloud, the system establishes real-time communication between users, bypassing the single-user limitation of VR and achieving a synchronized virtual environment.

The server relays all communication from one user to all users in the virtual environment. This application serves as the client for the virtual environment. Each virtual environment has a master client. A master client is responsible for synchronizing all object statuses with other clients and updating ownership of objects so that objects can be manipulated by other clients.

To achieve collaboration between users, the client application is developed with several key behaviors. The user in the client application can request the server cloud, in the scene, to create a new collaboration room or join an existing room. Figure 3 presents the application in the VR.
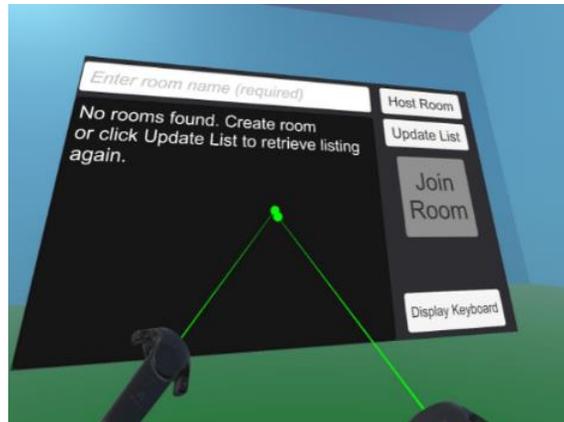


**Figure 3. Creating or joining collaboration room**

When the user joins the collaboration room, the client application starts sending and receiving data from the server cloud, which is the key basis for synchronized virtual environments. However, the client application will only send data when the user changes the object or environment states (i.e., orientation or location of the object). Objects in the virtual environment have ownership properties, which 'tell' the client application if its user has permission to manipulate them. To allow users manipulate all necessary objects, the client application requests the owner of the object to start the ownership transfer process at the start of object manipulation.

**HMD**

As mentioned earlier, HMDs was selected as the VR technology for the CVR application, specifically, the HTC Vive system (Vive). In Vive, the HMD and controllers are tracked in real-time using two IR sensors to manipulate the visualization and controller position in the virtual environment. Both controllers have clickable, haptic trackpad, triggers, grip buttons, application menu button, and a home button. These features of the controllers are used to manipulate objects and perform actions in the virtual environment.

**Simulation Engine and other Infrastructure Elements**

The CVR system architecture is illustrated in Figure 4. The Unity3D game engine was used for facilitating CVR. Unity3D is a cross-platform development engine that is widely used that supports various consumer VR HMDs and has an intuitive user interface that allow easy design of VR applications while providing rendering and scripting capabilities. Furthermore, Unity3D has robust VR support and vast collection of add-ons and assets readily available to developers. Also, features such as networking and VR mechanics can be implemented relatively fast. Finally, Unity3D has already optimized VR rendering techniques so developers can focus on building their application rather than dealing with low-level APIs.

Other components utilized for the CVR are the Photon Unity Networking (PUN), SteamVR, and the Virtual Reality Toolkit (VRTK). PUN facilitated the collaboration elements described above. Using PUN overcomes networking limitations such as narrow bandwidth limitations and eliminates the need to deal with low-level network APIs. Furthermore, PUN does not require server workstations since all networking communication is done between the users' VR workstations and Exit Game's server (https://www.photonengine.com/en-US/Photon).

SteamVR was used to facilitate VR in our application. SteamVR is a VR API that is compatible with different VR HMDs and exposes controller functions and rendering models to developers, allowing them to read button and trackpad states and use custom rendering models for the controllers. The VRTK software solution asset for the Unity 3D game engine provided a convenient platform for implementing physics engine, menus and other controls.
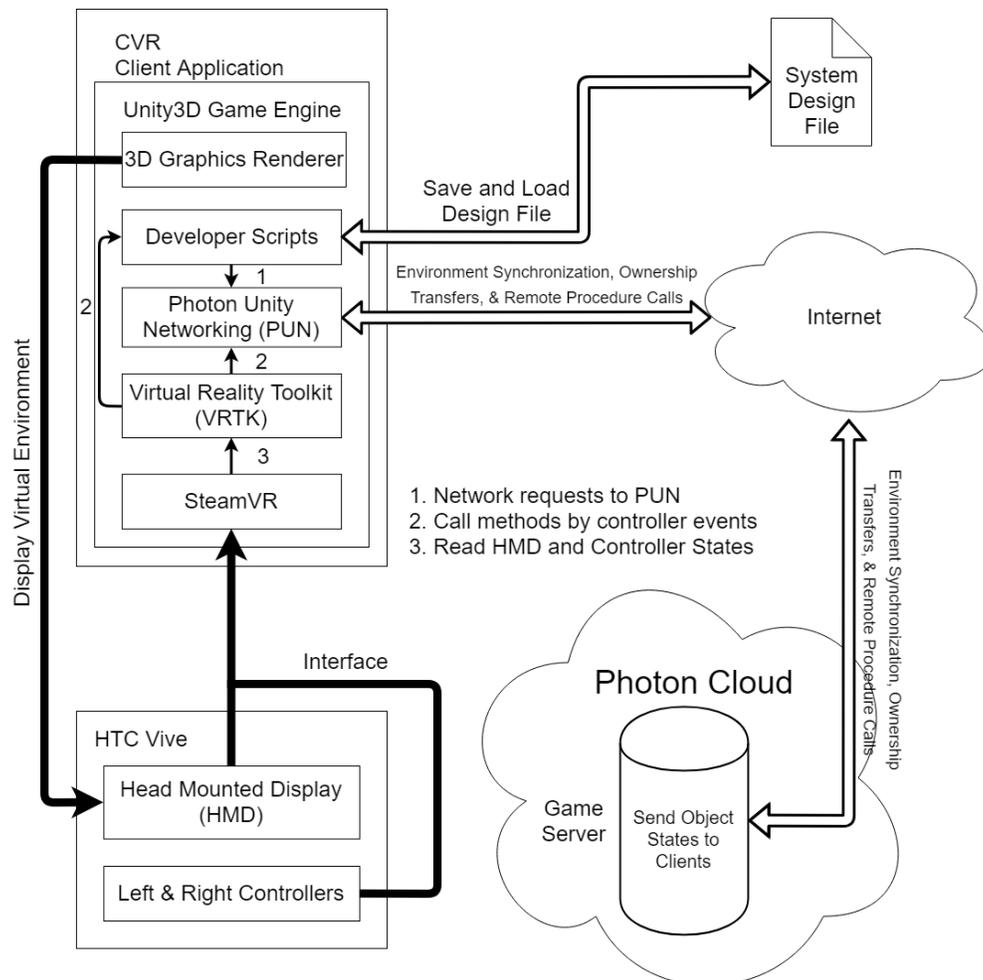


**Figure 4. CVR Architecture**

## CREATING INDUSTRIAL SYSTEMS WITH CVR

CVR herein was designed for the HTC Vive HMD system. In the Vive, the HMD and the tracked controllers facilitate the ability to interact and view the system from any desired point of view. Botvinick and Cohen (1998) suggest that virtual body ownership is a critical factor for immersion. Therefore, the controllers were presented as virtual hands in the VRE. The left and right controllers included VR menus for the users to 'spawn' system components to the VRE,

manipulate the components, and save and load the current system design. Figures 5a and 5b show the menus in the VR with the controllers represented as hands. To design systems in the VRE, all collaborators can spawn system components and connect them together. To spawn system components, the user places their thumb on the haptic trackpad on the right controller to bring up a radial menu as seen in Figures 5a and 5b.
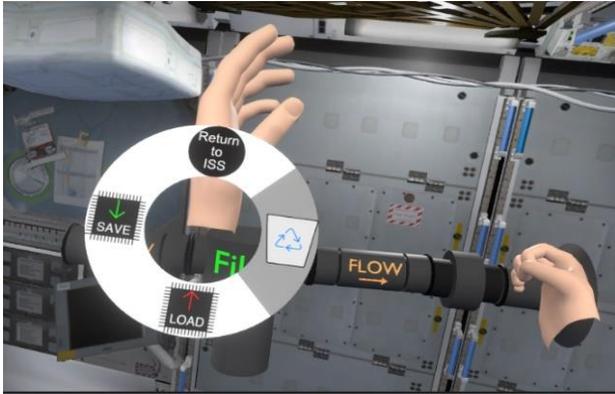


**Figure 5a. Left Hand Controller for Saving and Loading System Design.**
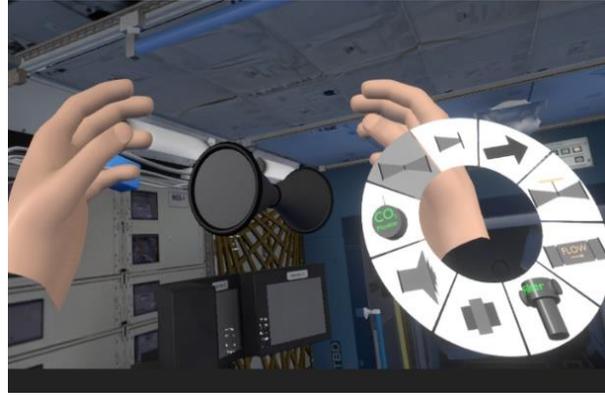


**Figure 5b. Right Hand Controller for Spawning Industrial Parts.**

The user then move their thumb to select the system component of their choice and press down on the haptic trackpad to spawn the component. The user can also use the trigger on the controller to grab the component and move it around in the virtual environment (see Figure 6). All components can be manipulated by any user in the virtual environment.
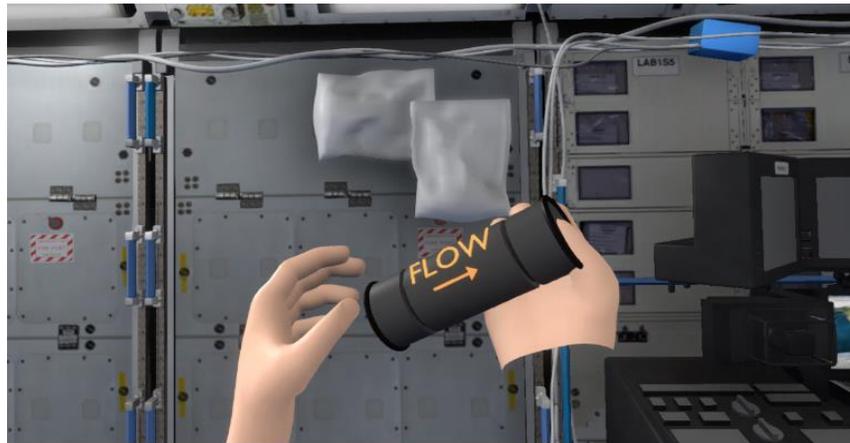


**Figure 6. Grabbing Components in CVR.**

## PILOT TESTING CVR

To pilot test CVR, we deployed the application as an assignment in a course titled Risk Analysis and Management at Iowa State University. The course consisted of senior level and graduate students. Curriculum consisted of introduction to the concept of risk, multiple risk assessment techniques such as Preliminary Hazard Analysis; Failure, Mode, and Effect Analysis; Event Tree Analysis; Fault Tree Analysis; and Human Reliability Analysis.

During the course, students interacted with former NASA astronaut, Clayton Anderson, and former International Space Station Flight Director, Tomas Gonzales-Torres, and reviewed information on risk in spaceflight operations. The authors herein developed a simulation for the International Space Station (ISS-SIM) as an interactive model for research purposes (Finseth, et al., 2018a,b; Finseth et al., 2016). Figures 7a and 7b capture ISS-SIM images. Furthermore, Figure 7a illustrate user-ISS model size ratio.
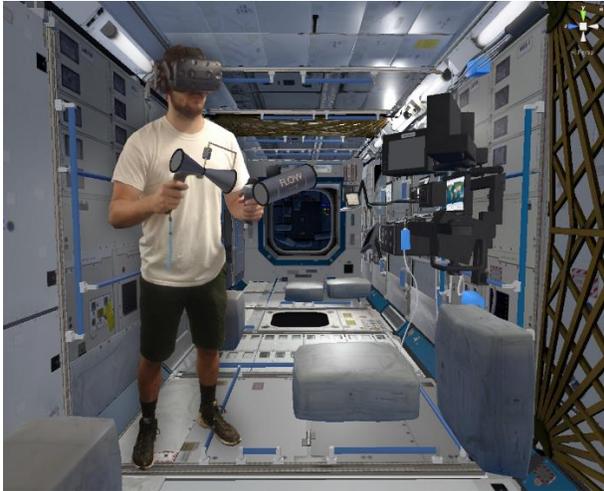
**Figure 7a. The US lab in the ISS-SIM.**



**Figure 7b. External View of the ISS-SIM.**

CVR was then implemented on the ISS-SIM. Students in the course were divided to five teams and were handed a problem statement with various material needed to work with CVR in the ISS-SIM. The following information is an extract from one of the projects:

**Problem Description:** Spacewalks can last up to 8 hours. Unfortunately, some operations require longer durations and the limiting factor becomes the oxygen supply in the EMU (spacesuits). NASA has requested that hose connections to be placed outside the A/L module to circulate extra oxygen and potentially lengthen the duration astronauts can spend making repairs.

**Team Task:** Build a system to monitor and transfer oxygen from the A/L oxygen tanks to astronaut spacesuits. The system should maintain pressure and temperature in the operating range. The ending hose for this system (i.e., where the spacesuit connects) can protrude from the exterior of the A/L module. The system should be able to support two astronauts at a time.

**VR Editor:** The VR system consists of an editor that allows you to build systems by choosing elements from a menu system and then place them in the station/space. A list of items that are available in the menu is attached herein. If you find that you need a component that is not available in the menus contact me and we will create it for you. You will have to save the system you created every time you finish (recommended to save every hour or so, so you do not lose a lot in case of a malfunction, e.g., power down). You will then have to upload it next time you are back in the system. Failure rates will be provided for you to work the risk assessment.

**Risk Assessment and VR design iterations:** Follow the process of developing a system as follows. Document each step in details: (1) Develop candidate concepts for the system. (2) Apply Preliminary Hazard Analysis (PHA) on the concepts and justify which concept to pursue based on the results from the PHA. (3) Develop the concept in details and create the system in the LAB with the VR Editor. (4) When completed take phots of the system. Title these images PFMEA# (Post FMEA); (5) Conduct Failure, Mode, and Effect Analysis on the system. Identify elements that require implementing countermeasure. (6) Implement the countermeasures based on your analysis. (7). Conduct 1-2 Event Tree Analyses and 1-2 Fault Tree analyses (cumulatively, at least three analyses) on the most critical events/faults you identified in your previous analyses. Document the results in details. (8) Implement modifications to the system you designed based on your ETAs & FTAs. (9) Take photos of the final system. (10). Write a comprehensive, final report that is based on the analyses you conducted and prepare a presentation for the class and for guest judges.

Table 1 presents a brief scenario, problem, and goal description for all five projects:

**Table 1. Problem and Goal Description for each Scenario**

| Scenario | Problem | Goal |
|---|---|---|
| Spacesuit Water Supply (SWS) Replenishment | An error in selection switch can pump urine and other waste fluids into the water reservoir in the spacesuits. | Build a system that will pump water into the reservoir and remove waste fluids from the suits. |
| Oxygen Supply Replenishment for Visiting Vehicles | Replenishing oxygen supply for vehicles requires to replace oxygen tank via spacewalk. | Build a system that monitors and transfers oxygen to oxygen tanks on the vehicles through a piping system. Temperature and pressure must be maintained within operating range. |
| Oxygen/Nitrogen Supply System for Crew Sleeping Racks | Circulating atmosphere is difficult due to microgravity, which can form hazardous pockets of carbon dioxide around astronauts' mouths. | Build a system for supplying oxygen/nitrogen to the sleeping racks. Must conserve oxygen/nitrogen during the day, extended durations at night, or when no compartments are in use. |
| Oxygen Supply for Extravehicular Activity (EVA) Drone | Refueling drones through spacewalks is costly and dangerous. | Build a system for supplying oxygen to EVA drones. Oxygen should be transferred from the drones if repair is required. |
| Exterior Oxygen Supply For Extended EVAs | Spacewalks can last up to 8 hours. Some operations, however, may require longer durations. Oxygen becomes a limiting factor. | Build a system that monitors and transfers oxygen to two astronauts' spacesuits. Temperature and pressure must be maintained within operating range. |

**DISCUSSION & LIMITATIONS**

This study aimed at helping novices form mental models for systems and pursue risk assessment processes. The paper presents a 3D, full-scale, highly interactive VR application titled Collaborative-VR (CVR) developed for creating and modifying industrial system layouts. Observations from a pilot study indicate that students struggled forming robust representation of the systems and, subsequently, gained limited success assessing risk, as described next.

While working in CVR, students were immersed in designing and building the system. Higher levels of engagement in safety training have been shown to subsequently increase the effectiveness (Burke et al., 2006; Wyk & Villiers, 2009). However, observations from this pilot study are that student's lacked experience with 'what a system is' and 'how systems look'. This observation supports the concern expressed early in this document that students, due to lack of experience, struggle to develop robust mental model for systems, and thus, it is expected that they will struggle in facilitating effective risk assessments. Results from research by Nasios (2002), who developed a computer-monitor VR environment to train personnel for centrifuge pump hazard identification, are consistent with the observations herein. From Nasios's research, the University of Nottingham created an interactive learning environment for university students with three different modules related to component identification, hazard identification, and procedural operation. For the students, a VR training system was more effective at transferring knowledge due to increased familiarity with spatial and time relationships. Nasios's findings are consistent with this pilot study which conclude that a paper and pencil approach created difficulty in understanding and identifying system precautions.

It was further observed that students significantly emphasized system functionality in their design to an extent that risk analysis was a secondary priority. While all teams were engaged in risk assessments, more than half of the teams failed to use the Risk Assessment Matrix, a tool they had used consistently in class activities and take home

assignments. It is important to note that the VR experience was not announced in the syllabus, but was added early in the semester. Thus, some students expressed concern with the extra efforts required to complete the project. However, the novelty of using a CVR environment may have temporarily inflated the student's self-assessment of their ability to identify risks in lieu of traditional risk-assessment tools.

Several limitations were encountered during the pilot study that limit the technical capabilities and the generalizability of the observations. CVR is designed to visually assess risks; it cannot utilize other sensory information such as touch and smell to analyze more risks in the system. HTC Vive used for CVR does not feature capabilities to simulate touch or smell. Other VR technologies such as CAVE$^{TM}$ may also not feature touch and smell capabilities (Puschmann, et al, 2016). Potentially, implementing transmission of signals though haptic or olfactory channel may enhance risk assessment on industrial systems. HTC Vive, however, does feature audio capabilities and it can be utilized to enhance risk assessment via audio sensory information, but it was not implemented in CVR.

VR for risk management require users to mentally translate the VR environment back to the system design. This takes a significant mental effort to account for all features and structures of the virtual environment into the system design, especially when the virtual system does 'nothing' (i.e., there is no output from the system once created). While VR can increase visual fidelity to find more flaws in system designs, it can also increase visual detail irrelevant to the risk assessment, which may defer attention away from more critical design flaws (Puschmann et al., 2016). In CVR, system components models were designed to be simple and identifiable for the purpose of training students in risk assessment. Using more complex models may not help trainees without risk management experience develop more optimal mental models for their system. Users experienced in risk assessment, however, may find complex models to be more beneficial (Puschmann et al., 2016).

From technical perspective, several improvements could significantly enhance user experience in CVR and its toolsets. First, objects put together did not flush with each other, and as a result, the industrial system did not look elegantly built. This issue was resolved by implementing an object snapping algorithm. Object snapping allows user to place objects next to each and the client application snaps the objects together at the correct angle, creating a more visually coherent system. Second, the saving/loading interface needs to be enhanced for user-friendliness. Third, an auto-save function needs to be deployed. In a couple of cases, system designs were lost due to software failure mid simulation. Fourth, certain elements in the design user interface, such as deleting object, could be improved. A tool for measuring TSMM should be implemented in order to capture the impact of CVR to the three components of shared mental model (i.e., knowledge representation, structure representation, and representation of emergence) as an indication for its contribution to team risk assessment process and performance. Finally, as indicated earlier, the fact that 'nothing happens' when the systems are built was frustrating; that is, student expected to observe a working system. Solving these technical challenges may enhance user experience and aid knowledge transfer to students.

**CONCLUSION**

Understanding the extent to which applications such as CVR can enhance trainees risk assessment skills requires further research, development, and validation. Conducting risk assessments require robust understanding of the system at hand. Trainees without previous industrial experience will usually struggle with conceptualizing industrial systems and thus are less likely to develop a strong grasp of risk assessments. The efforts herein suggest that CVR has a potential to enhance trainees' mental model of systems, a challenging issue as described above. Further efforts, where individual and team shared mental models are assessed, will add much needed insight to state of students' system conceptualization.

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