

Virtual reality for transportation incident management training of first responders in remote areas

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ABSTRACT

Training volunteer firefighters in remote areas on major transport incidents, such as train derailments containing dangerous goods, is challenging on many levels. Even though these incidents are rare, their consequences can be damaging for local communities, the environment, and the transportation supply chain. A report (Transport Canada, 2015a) indicates that firefighters are not adequately trained for large scale train incidents involving dangerous goods, that they do not have the necessary skills to use specialized equipment, and that small and remote communities have limited capacities to respond to these incidents. A main issue is that the training expertise is often located in urban areas, which suggests that a technology-based approach could offer an essential element to increase first responders' awareness, operation, and command knowledge and skills. In this respect, Virtual Reality (VR) offers a potential alternative to training methods such as web-based e-learning solutions, allowing for realistic and safe simulation of a wide range of dangerous fire scenarios. In addition, the capability to bring multiple users into a shared VR space enables team training, and remote instructor feedback and support. The paper reports on our progress in the development of a VR training environment where a novice first respondent is acquiring situational awareness of a train derailment while interacting with an intelligent tutoring system. The system is being developed with off-the-shelf and open source components including Oculus Rift S, Unity, and options are being explored to implement adaptive instructions, including the Generalized Intelligent Framework for Tutoring (GIFT) (ARL-HRED, 2012). The paper also presents how the different elements of the adaptive instructional system are implemented in the GIFT architecture including the user interface, as well as domain knowledge, learners, and pedagogical models.

ABOUT THE AUTHORS

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INTRODUCTION

Training volunteer firefighters in remote areas for major transport incidents, such as train derailments containing dangerous goods, is challenging on many levels. Even though these incidents are rare, their consequences can be damaging for local communities, the environment, and the transportation supply chain. A report from Transport Canada indicates that first responders are not adequately trained for large scale train incidents involving dangerous goods and do not have the necessary skills to use specialized equipment (Transport Canada, 2015a). Consequently, especially small remote communities have limited capacities to respond to these incidents. A main challenge to mitigate the aforementioned issues is that the training expertise is often located in urban areas. Therefore, technology-based approaches to instruction could offer essential support to rural and remote first responders to increase their awareness, operation, and command knowledge and skills.

This paper reports on the progress in the development of a virtual reality (VR) training environment for novice first responders. Trainees acquire situational awareness, knowledge and skills required to deal with a train derailment, or other major transportation incident, while interacting with either a remote instructor or an intelligent tutoring system. The first section of the paper states the problem, followed by a review of prior work, a description of the indented solution, including stakeholders' needs and system requirements, system overview, and system evaluation plan. Finally, the paper summarizes the main results in a conclusion.

PROBLEM STATEMENT

Transportation of dangerous goods on rails is relatively safe compared to other modes of transportation. For instance, in 2017 only 11 out of nearly 400 reportable incidents, or less than 3%, involved transportation of dangerous goods via rail (Statistics Canada, 2019). Similar incident rates have been reported in other jurisdictions (Eurostat, 2017; U.S. Department of Transportation, 2019, 2020). However, as illustrated by the crude oil rail fires in Lac Mégantic QC (Transportation Safety Board of Canada, 2014) and more recently in Guernsey, Saskatchewan, Canada (Transportation Safety Board of Canada, 2020) (see Figure 1 for an image of the latter), even these rare incidents can have a highly negative impact. As such, it is imperative for first responders need to be prepared for these types of incidents. According to the National Fire Protection Association there is approximately 152,650 firefighters in Canada during the period 2014 to 2016, of these, 17% were career firefighters and 83% were volunteer firefighters (Haynes & Stein, 2018). This large proportion of volunteer firefighters highlight the need to provide efficient remote training.

A report by the Emergency Response Task Force (Transport Canada, 2015b) noted that “large, industrial scale, flammable liquid firefighting is not a service that most fire departments have been trained or equipped for [...]. The significant increase in volume of flammable liquids transported in unit trains moving through hundreds of Canadian communities in recent years has introduced an important risk that fire departments are not prepared to handle”. This report further notes that:

- firefighters were not adequately trained for large scale train incidents involving dangerous goods;
- first responders did not have the necessary skills to use specialized equipment for said incidents; and
- small and remote communities have limited capacities to respond to said incidents.

Given these circumstances, one important question is: How can first responders in remote areas efficiently and effectively train for low-probability but high-impact incidents involving transportation of dangerous goods?



Figure 1 Aerial photograph of train derailment, fire and spill near Guernsey, Sask. Image by Philippe Gaudet (Canadian Broadcasting Corporation, 2020).

PRIOR WORK

VR and other immersive 3D user interface technologies offer a potential alternative to training methods such as face to face, and web-based e-learning solutions, allowing for realistic and safe simulation of a wide range of dangerous goods transportation incidents and fire scenarios. In addition, the capability to bring multiple users into a shared VR space enables team training, and remote instructor feedback and support (Aameer R. Wani et al., 2013; Kinateder et al., 2014; Yang et al., 2018). VR training tools for firefighters have been developed since the late 1990s (Bliss et al., 1997; Tate et al., 1997). More recently, VR training tools have been developed for complex scenarios such as airborne wildfire fighting (Clifford et al., 2018), and experimental research explored the relative comparison between training in vivo and in virtuo (Narciso et al., 2019; Yang et al., 2018). A systematic review discussed VR training for firefighters using a SWOT analysis approach listed the following strengths, weaknesses, opportunities and threats (Engelbrecht et al., 2019):

Table 1 Results of the SWOT analysis presented by Engelbrecht et al.

Strengths	Weaknesses	Opportunities	Threats
<ul style="list-style-type: none"> • Cost effectiveness • Complex and varied training scenarios • High ecological validity • Increased safety for high risk training • Trainee engagement—Data recording 	<ul style="list-style-type: none"> • Lack of specialization and testing of systems • Immaturity of technology • Technology barriers • Lack of multi-user fidelity 	<ul style="list-style-type: none"> • System engineering progress • Transfer of findings from other domains • Increase in physical fidelity • Increase resilience against adverse effects 	<ul style="list-style-type: none"> • Uncertain skill transfer • Worsening of overall net effects of training • Adverse effects of habituation • Adverse effects of engagement stimulation

In combination with VR, one technology that can support effective training for firefighters is real-time voice interaction between trainees, instructors, or intelligent tutoring systems (Kondratova & Emond, 2020). In fact, it is projected that conversational platforms will drive the next big paradigm shift in how humans interact with the digital world and simulations (Cearley et al., 2016; Klopfenstein et al., 2017). Currently, conversational interfaces are mostly implemented in spoken or written natural language. In time, other input/output mechanisms will be added to exploit sight, taste, smell and touch for multi-channel interaction. Increased sensory and haptic feedback in VR is pertinent to learning tasks involving fine motor control, which is particularly relevant in situations related to emergency response (Brown et al., 2020; Dangxiao et al., 2019). Multisensory cues have been demonstrated to increase performance in VR and is more highly rated as a subjective experience (Cooper et al., 2018). Expanded sensory

channels will support advanced software capabilities, such as emotion detection through facial expression analysis, which could be very relevant for first responder and firefighter training, to detect the trainee's stress response. Emotion detection could enable delivery of better feedback during training and real-time training modifications based on trainees' responses (Goldberg & Cannon-Bowers, 2015). Already, a combination of speech with other input modalities (such as gesture, gaze, etc.) offers a flexible and integrated set of interaction tools for Augmented Reality (AR), and Virtual Reality (VR) training applications (Emond et al., 2018, 2016; Stedmon et al., 2011). Our previous work in developing voice interaction for serious gaming was acquired in several development projects for voice enabled military and law enforcement mixed reality training (Fournier et al., 2011, 2012). Results of our research indicate that speech-based interaction is critical in ensuring the realism of the interaction with the virtual environment. The accuracy of speech recognition can vary significantly across training conditions. However, it can be compensated for by using complementary modalities, such as touch, gaze, gesture or manual controls.

PROPOSED SOLUTION

The project is at an early development stage. Based on the literature review and initial identification of stakeholder needs, the project aims at producing within a year a virtual reality (VR) training prototype for novice first responders. The project is engaged in parallel activities of gathering needs and system requirements as well as laying the technological foundations of the training system. Of particular interest for the requirements collection efforts is to determine how to integrate intelligent tutoring capabilities and remote instructor input to trainees' sessions. The evaluation plan includes various means to proceed with the evaluation of products at different stages of development, being a vision for the product, a validation of a need assessment, software usability, and software validation (fit for purpose). Given the current limitations affecting face-to-face meetings and product evaluation sessions, alternative methods for remote evaluation will be applied during the course of the project.

Stakeholders Needs and System Requirements

To identify stakeholders' needs and system requirements, searches of relevant scientific literature will be conducted using the Federal Science Library, a single portal for scientific information from seven science libraries in the government of Canada with a two billion item citation index, including hundreds of resources such as SCOPUS and NTIS. Key findings from the scientific literature, guidance documents, relevant standards, such as the NFPA (National Fire Protection Association, 2017) and reports will be reviewed and synthesized in order to formulate user needs and recommendations for technology development.

In addition to the literature review, user needs and technology requirements will be elicited through stakeholder engagement activities such as a series of semi-structured interviews, and an online survey to be sent to pre-identified stakeholders. These activities will identify a list of broad range of requirements for technology supported training of first responders in remote areas in the management of major transportation incidents, and will help to find stakeholders that are interested to collaborate on the project. The project will also hold a series of sessions with key stakeholders for the specification and refinement of a minimal valuable product definition (Fagerholm et al., 2014). Stakeholder groups will include fire chiefs from career and volunteer fire departments; firefighter trainers (who also tend to be firefighters themselves); firefighters (career and volunteer with different levels of experience, from both rural and urban areas); and policy makers such as the National Fire Protection Association. The NFPA has worked with the Council of Canadian Fire Marshals Fire Commissioners (CCFMFC) and the Standards Council of Canada (CSS) to provide vehicle safety training for emergency responders to Canada.

System Overview

The system is being developed using both a user-centred methodology of continuous experimentation (Fagerholm et al., 2014), and a component-based software development (CBSD) paradigm. CBSD proposes to accelerate software development and reduces development costs by assembling systems from existing components. Component based development includes option of purchasing components from the market (or use open source solutions), or if the market does not offer what is needed, engage in component development (Brownsword et al., 2000). The targeted hardware is composed of off-the-shelf VR systems such as the Oculus Rift S.

The 3D modelling and the development of training scenarios will be done using Unity. Depending on the training scenarios, virtual scenes will vary in terms of types of transportation vehicles (trucks, trains), types of dangerous

goods, transportation infrastructure near the incident (roads, rails, overpass, bridges), as well as day light and weather conditions. The 3D scenes will also be programmed to capture the position of the avatar representing the person in training so that affordances for the execution of user actions can be associated to specific locations and assessed in context. A virtual version of the Emergency Response Guidebook (Transport Canada, 2020) will also be made available for consultation in the VR environment.

To improve the realism of user interaction, the system would incorporate voice input as a natural mode of interaction. The system could initially focus on the application of speech recognition and synthesis technologies for novice trainees in order to reduce the size of the required vocabulary, and restrict the scope of the training dialogues. Adding additional interaction modalities such as touch or gesture could improve user experience and engagement with the system. The system would deploy a modern speech recognition software with customizable grammar and vocabulary, since in first responder communications it is typical to use discrete word commands within a constrained and specified lexicon instead of continuous speech. The lexicon for the application will be developed in close collaboration with the intended users of the system. The grammar lexicon for the simulations will also include gestures and other commands. In case of limited network connectivity, an off-line speech recognition engine (not cloud-based), that is updated periodically, will be available. Considering Canadian context, speech recognition will be bilingual (e.g. accommodating both French and English-speaking trainees). In addition, speech recognition training could be used in the context of strong regional accent. Voice interaction design and implementation for the user interface will follow HCI guidelines for the successful use of voice interaction in training applications (Kondratova & Emond, 2020).

The software development team is also exploring different alternatives to provide adaptive instructions using an intelligent system to represent of the domain knowledge, use pedagogical strategies, maintain learner models, and communicate with the user through the user interface. Options for supporting those intelligent tutoring modules include the Generalized Intelligent Framework for Tutoring (GIFT) (ARL-HRED, 2012), as well as a solution based on knowledge graph implementation based on Common Logic (ISO/IEC 24707:2018(en) & Information technology, 2018), the Knowledge Interchange Format (Genesereth, Michael, 1992) and conceptual structures (Sowa, 1984).

Evaluation Plan

The main goal of our work is to provide first responders with a training tool that will enable them to practise otherwise dangerous tasks in a safe and controlled environment. In order to achieve this goal, we explored previous literature that has identified certain standards that should be included when evaluating the quality and effectiveness of the virtual environment. The project had planned various means to proceed with the evaluation of products at different stages of development, being a vision for the product, a validation of a need assessment, software usability, and software validation (fit for purpose). Some of these phases are closely connected and therefore some overall is expected. Usually, the most preferred option for the evaluation is the physical presence of the participants. However, the current pandemic is causing the project to explore different alternatives for capturing evaluation data, which we describe in the following sections.

Data collection—Evaluation process during the stages of tool development

During the “**designing the tool**” phase we will conduct a series of workshops to discuss the main vision for the product capabilities with small set of people from key areas. This special interest group, also called advisory group will be able to provide the project team with guidance on future directions for the VR tool design. The members of the advisory group are being selected based on the expertise of organizations or individuals in relation to this research and their interest in this work. During the workshops, project team will facilitate the discussion and record comments and feedback in regards to overall research work, the development and assessment of the VR tool, and any future dissemination of the result for public release. The project team together with the advisory group will be able to explore and address any future questions that might arise from each set of designs and scenarios. The workshops will be done via videoconferencing tools where the project team and the advisory group will be able to discuss all necessary aspects of the research process and software tool design. The main aim is to also provide advice on future communication strategies with wider groups of stakeholders (survey).

In the next phase of the evaluation process we will conduct a “**validation of need assessment**”. This phase is closely linked with the previous phase as the communication with the advisory group will be ongoing. This process is designed to determine priorities and importance for particular groups and make necessary improvements in the design. In this

stage we will be sending out surveys to a wider group of identified stakeholders (fire departments, firefighters, etc.). The survey is designed to identify the first responders training needs such as learning of new strategies and technical skills necessary to address various hazardous scenarios, as well as identify the main design requirements in terms of key features available and potential risk and benefits for each scenario. The collected survey data gathered from a wide range of stakeholders will be analyzed and the results will be further discussed with the advisory group. During these discussions, we aim to identify solutions and advancements for the tool to address main areas targeted to relevant stakeholders' group. These data will be used for the further optimization of the VR training tool.

When our VR training tool design is finalized and completed, we will proceed to the “**software evaluation**” phase which will be conducted by adopting a user-centric approach to evaluation. For this phase our preferred method for the evaluation process would be in-person evaluation/testing that would be conducted with most recent health and safety guidelines in effect. During this time participants will interact in VR environment and a number of quantitative and qualitative metrics will be collected. The quantitative metrics that will be collected might include overall completion time for the given task or individual phases, number of errors observed or reported, or any other relevant task completion metrics. Previous literature shows that virtual reality environment usability evaluations are raising unique issues due to the immersive experience of the user (Cooper et al., 2018; Karre et al., 2019). We therefore aim to collect a number of qualitative metrics that will include perceived sense of presence, cyber-sickness including fatigue and nausea, perceived cognitive workload, and perception of stress. Both sets of these data will be collected from each participant. The final study design is still need to be determined but we are open to idea of also incorporating pre- and post-evaluations of given scenarios or conducting a comparison study between a number of different scenarios. Other means for data collections will also be explored and implemented mainly through focus groups and interview with participants, either in-person, whilst adhering to health and safety regulations, or via videoconferencing methods.

However, as there is a possibility that the in-person testing will be unfeasible due to current pandemic uncertainties, we are exploring other possible evaluation procedures. Our approach is to design an evaluation plan that enables remote evaluation through a range of options, including synchronous and asynchronous evaluation, where the usability engineer and the respondents will be separated in space and possibly in time as well (Fidas et al., 2007). Synchronous evaluations are usually performed in conjunction with a videoconference session. Asynchronous evaluations use other methods such as automatic users log analysis interpreted as representing task trees (Harms, 2019). In these cases, we propose to reach out to potential participants who already own VR headsets at home and they will be invited to participate in the evaluation studies remotely in an empirical test (similar to Mechanical Turk approaches). As before, a number of qualitative and quantitative metrics will be collected via remote automated evaluation. There is a possibility that this avenue might be more promising compared to pre-pandemic times as sales of immersive headsets have spiked in recent months. However, we also acknowledge that this approach might come with certain limitations and constrains i.e. not all participants/first responders will have access to VR technology/equipment. We aim to continuously explore all options for data collection for all software evaluation phases in order to obtain a rich data set that will enable us to quantify the effectiveness of the tool and enable us to propose evidence-based conclusions and recommendations.

As the essential element of an experimentation approach to software development is the capability to evaluate different hypotheses, our “**software validation**” phase will focus on interpreting the collected data in relevance to proposed assumptions (Fagerholm et al., 2014). Once the design of the tool and the training scenario are finalized, we will to form a number of hypotheses addressing the tool effectiveness in terms of satisfaction, usability, interactivity, as well as overall performance. As the main objective of any VR training is the ability to learn skills that can be later transferred to real life scenarios, we aim to address the ability of the tool for training transfer from virtual to real environment (Bliss et al., 1997). We plan to follow up with participants with regular updates about the learning transfer applicability of the VR training tool. From a previous discussion with our stakeholders we recognized that it is important for them to be able to measure skill retention during and after the training, which helps learners to internalize main points and facts for strategic problem solving. We will therefore use these updates to validate whether the skills learned during virtual training was transferred to real-life scenarios. The potential of the tool to be used as a training tool for refreshment training is also foreseen. All of the data collected during this phase will be used to validate the software tool and if necessary provide further guidance to optimize the overall software tool usability and performance.

CURRENT STATE OF DEVELOPMENT

As outlined in the previous sections, the system development and evaluation plan are closely linked. Depending on the state of development, different evaluation methods are required to support design decisions. For the initial prototype development, the project used a cognitive walkthrough method by stepping through simple transportation incident scenarios in order to evaluate the ability of the training environment to support each step (Jankowski & Hachet, 2012). The method allowed to identify the need for interaction objects such as binoculars, a phone, the standard emergency guide book, and a system of notification zones that can generate messages to the screen, indicating when an event occurred like the presence of smells or heat (Figure 2). The notification zones can also trigger learner performance measurement events such as when the dangerous material placard is visible and the identification of the product is possible given that the learner is at proximity. Associated with the phone are configurable dialogs through XML files which specify communication options with emergency authorities.

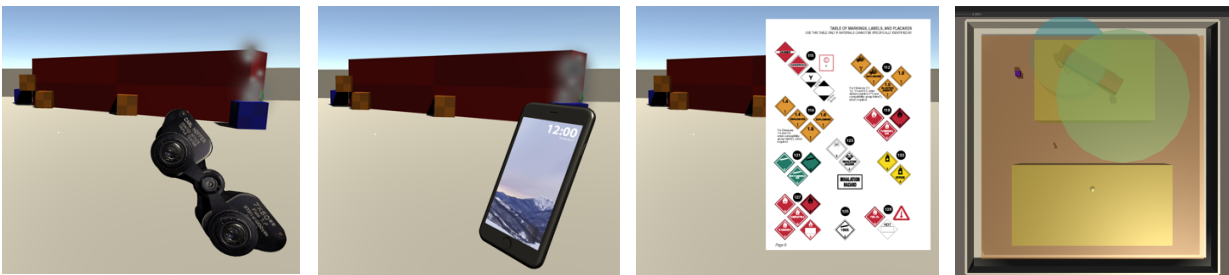


Figure 2. From left to right: binoculars, phone, the emergency guide book, and bird's-eye view of invisible notification zones.

The software development proceeded with the concurrent construction of two versions of the system. One focused on the identification of essential interaction elements to support task execution, and a second version focused on high-fidelity visual objects. The two versions are to be merged in the next software development iteration. Figure 3 A and B provide examples of each of the version.

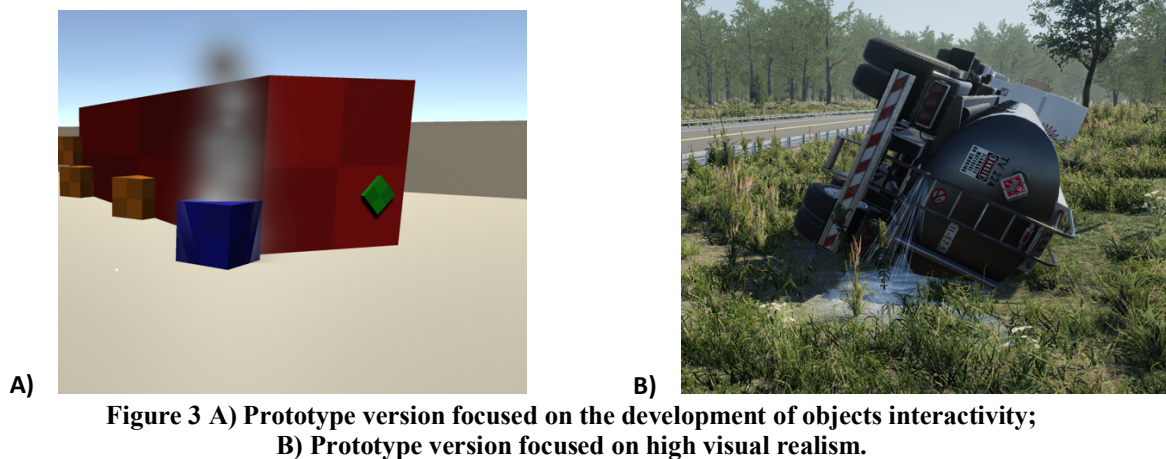


Figure 3 A) Prototype version focused on the development of objects interactivity; B) Prototype version focused on high visual realism.

In addition, the training environment includes a representation of scenario task sequences as a set of related nodes that are used to trace, measure, and evaluate the performance of a learner while engage in an opened-ended transportation incident scenario. Next steps for the development of the training environment include the merging of the object interactivity with the high-visual fidelity software versions, as well as the integration of a network component for the remote storage of learning performance data.

CONCLUSION

Training volunteer firefighters in remote areas for major transport incidents, such as train derailments containing dangerous goods, is challenging on many levels. Even though these incidents are rare, their consequences can be

damaging for local communities, the environment, and the transportation supply chain. This paper reported on the progress in the development of a virtual reality (VR) training environment for novice first responders. VR and other immersive 3D user interface technologies offer a potential alternative to training methods such as web-based e-learning solutions, allowing for realistic and safe simulation of a wide range of dangerous fire scenarios. The project is at an early development stage, and aims at producing within a year a virtual reality (VR) training prototype for novice first responders. The project is engaged in parallel activities of gathering needs and system requirements as well as laying the technological foundations of the training system. Of particular interest for the requirements collection efforts is to determine how to integrate intelligent tutoring capabilities and remote instructor input to trainees' sessions. The evaluation plan includes various means to proceed with the evaluation of products at different stages of development, being a vision for the product, a validation of a need assessment, software usability, and software validation (fit for purpose). Given the current pandemic, the project is planning to use synchronous and asynchronous remote evaluation methods to inform the development process.

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