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Simulation-based Virtual Reality Training for Firefighters

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Abstract

Simulation-based training is used to improve learners' skills and enhance their knowledge. Recently, virtual reality technology has been exploited in simulation mainly for training purposes, to enable learning while performing simulated activities that are dangerous or even impossible to be simulated in the real world. In this context, we present a simulation-based firefighter training for an earthquake scenario developed in collaboration with national Italian firefighters rescue units (Italian "Istituto Superiore Antincendi"). The proposed training model is based on a virtual reality solution and foresees a novel interaction and game model developed specifically for training first-responders. The simulator environment is a head-mounted display where the learner interacts with objects and performs specific tasks. The performed test show that the use of virtual reality can improve the effectiveness of training. Indeed, trainees show a better perception of the scene which is reflected in a faster response in the real situation. The proposed training system can help the firefighter by providing adequate information on how to deal with risks.

Introduction

Due to the high complexity of the intervention scenario (fire operations, landslides, tsunamis, and earthquakes), the design of effective systems for training first responders can be considered a relevant issue. For example, in cases such as earthquakes, firefighters have to move in a hostile environment to carry out a rescue. In situations where operations can be planned in advance, operators take training courses. Traditional training methods rely on previous real life experiences to define intervention procedures. In more details, firefighters can learn about the internal structure of a particular building by studying its actual designs or by following protocols for search and rescue. In this case, a possible rule is to maintain contact with the left or right walls when searching first in the perimeter of the building and then in the interior rooms. In recent years, Virtual Reality (VR) technology has been considered as a way for improving training. In fact, advancements in computing technologies and in rendering devices enable to enhance the interaction of physical objects to the ubiquitous virtual world. To this aim, simulation-based on VR have been exploited for training purposes, especially for dangerous or even impossible to be achieved in the real world scenario. In [2], a system for improving the effectiveness and users' appreciation of usability and usefulness in game-based learning is presented. Accordingly, VR solutions based on simulations are 3D simulations of an environment that allows the user to interact with the content of that environment [3,9] in order to learn how to perform a specific task. Lu, et al. [10] propose a simulation for an indoor post-earthquake fire rescue scenario. the framework focuses on the model of buildings while neglecting the performance of players in a VR environment. Thus, this simulator is used to data visualisation more than interaction with objects. In [12], a thermal stimulus for firefighter training scenario focuses on the performance of tasks and its impact on trainees while ignoring the design of the VR environment. In [4], a method for experiencing dangerous fire environments and performing training and evaluation by using a VR Engine is defined. Heldal et al. [7] provide a simulation for firefighter training, that includes incident commander training. It examines key elements recognized by user organizations that can counteract potential obstacles and challenges of simulation implementation. A literature review in [5] presents evacuation research studies conducted as VR Simulations, which succeeded on their pedagogical and behavioural objectives. Feng, et al [6] define a customization framework for VR for an earthquake emergency training by adopting the concept of adaptive game-based learning. Based on a house fire scenario, Oliva, et al. [13] did not focus on the sensory cues in the design of a virtual firefighter command training environment.

Despite the existence of several cutting-edge VR technologies for improving the User Experience (UX), several challenges hinder the widespread use of VR. Among these, the usability of a VR system is still under investigation. According to ISO 9241-11 [8], usability is defined as the ”Extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use”. However, some VR environments barely resemble the real situation. In this context, we present a simulation-based firefighter training system developed in cooperation with the Italian Fire Academy (Italian "Istituto Superiore Antincendi"). The design of the system copes with two aspects: to provide accurate interfaces for the rapid development of an after-earthquake scenario based on a real building model and to analyze the human behavior and capabilities through usability and UX in a satisfying manner for assessing simulation-based VR in firefighters scenarios. Moreover, systems exploiting immersive virtual technologies in simulations should not only support performing and learning tasks, but also allow large and complex data visualization for improving the interaction in the training system.

The rest of this paper is organized as follows: section presents a model as a guideline for designing the VR training. This model consists of three phases which are a collection of requirements, contexts, and objectives. In Section , we define the evaluation and the discussion of the proposed training. Finally, concluding remarks are presented in Section .

Simulation-based VR training for firefighters

The main goal of this research is to train first responders in a safety-critical scenario and compare the effectiveness of such training with respect to traditional document-based training. Therefore, a model is needed to create an appropriate training by providing adequate information on how to deal with risks. This can also improve future research carried out in operative control rooms. Based on the limitations of the existing training for the first responders (the firefighter in our case), we describe the phases related to requirements, environmental issues, and objectives information collection. This phase need to be completed in order to improve the training. Our analysis foresees three steps which are: collecting requirements, contexts and objectives (as shown in Figure 1).

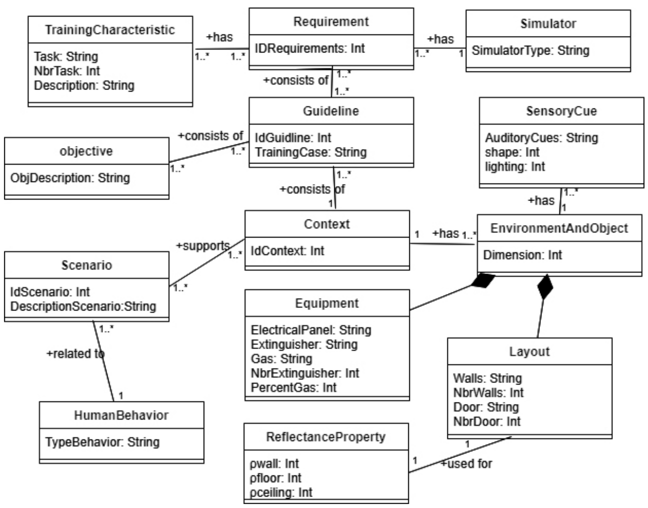

Figure 1. *Meta model specification of guideline for training.*

Collection of requirements

The VR training includes a simulator environment as well as a game design and content. The game content has been developed using the Unity game engine [1]. This engine supports the highly specialized hardware environment that has been developed. The rendering system for the simulator environment of our training model is a Head Mounted Display (HMD) [11]. More specifically, we adopted and HTC Vive. The player is surrounded by two tripods that support stations covering the majority of the field of view of the virtual world. A teleport mechanics was adopted to enhance the player's movement as well as to control the camera when the player is crouching. When the player is picking up an object, the teleport mechanics will help him to move while performing another task.

The use case of an earthquake situation was proposed by Italian firefighters' curators. The intervention is requested following a strong earthquake, which occurred after a previous earthquake that can cause some disruption of the supporting structure of the building, for which provisional shoring works will be carried out. The intervention is necessary following a gas leakage with the consequent development of a principle of fire, developed in the basement, in which there are gas supply pipes related to the heating plant serving the heating system of the building. The basement contains an archive of documents and goods of great historical, cultural value and an inert gas extinguishing system, of which it is necessary to ascertain the conditions of damage and carry out the necessary safety measures. Hence, seven tasks have been developed for the game of which one is a tutorial training on VR hardware and other six tasks introduced to perform the task provided by firefighters' curators. The remaining 6 tasks have been designed for the operational procedures of firefighters in an earthquake. Table 1 gives a brief description of the game tasks and the learning objectives behind them. A tutorial is used to train firefighters on VR hardware.

Tasks of the training and their learning objectives.

Task	Challenges	Objective and storytelling
0	Tutorial: instruction to use the device	Learning how to use HTC Vive device in order to reach the game's objectives
1	Electric panel	Turn off electricity power to the basement
2	Alarm system	Turn on the alarm system
3	Heating plant	Turn off gas power
4	Fire extinguishers	Pick up and use the right one
5	Gas suppression system	Visualize data and read clearly instructions
6	Wooden structure	Verify the compliance of the previous shoring works with the structural requirements

Collection of context

A scenario has been simulated in which a group of firefighters enters a basement of firefighters which is located in Italian firefighters rescue units. Two types of training for this task have been prepared: one is the typical training that the firefighters undergo which is based on paper instructions, the second is based on the use of VR. Thus, we had to design the same environment for of firefighters in the virtual environment. The layout of the firefighter basement was measured and planned. The basement had internal dimensions of 10.7 m x 6.2 m and a floor to ceiling height of 3.4 m. Munsell values [14] are used to estimate the reflectance properties. The internal walls of the room had reflectance (ρ) properties: $\rho_{wall} \approx 0.4$, $\rho_{floor} \approx 0.1$, and $\rho_{ceiling} \approx 0.1$. The sensory cues such as auditory cues, visual shape of the environment, visual lighting can affect the perception of the surrounding environment. With the gained knowledge about the processes used in the critical situation from the viewpoint of the firefighters' curators, the shapes and colors of the basement as well as the lighting rate are well-known aspects that have a strong influence on the attitude and reaction of trainees, performing training in an unknown environment can become an annoying experience independent of its well-created tasks. The proper lighting can improve task performance, enhance the appearance of an area, or have positive psychological effects on trainees. During the process of measuring the real environment, the basement was dark and thus, the illumination level was measured to define similar levels in the virtual environment for trainees. As a result, they can feel familiar with the real environment through the VR training and perform tasks even in a dark basement without an illumination problemar. This can interpret that VR has the capability to generate "realistic scenarios" that in turn create more "realistic feelings" in trainees (as shown in Figure 2.a and 2.b). Furthermore, the rapid change of visual objects and location in VR environment reduces the time of performing the experiment which helps to overcomes the limited settings when real environments are used.

Figure 2. *(a) Real environment. (b) Virtual environment.*

Collection of objectives

The use of VR can allow the trainees to remember performed tasks, and the process of tasks through following instructions in the VR training (as shown in figure 3). In addition, attending the objective of the training requires to classify the potential tasks. For instance, the data visualization tasks (5 and 6) which are related to read instructions and verify the compliance of a shape are related to clear content information, design and comfortable features. This can help to evaluate the performance of tasks. The third and fourth tasks are more important than others and relate each task with the corresponding usability features. This aids to evaluate the result. For instance, in tasks 2, 3 and 4, participants can interact with game objects. However, in tasks 1, 5, and 6, the participants can only visualize the data and perform the instruction in a real environment.

Figure 3. *Screenshots of the virtual reality-based system designed for firefighters training. On the left side, firefighters can verify the compliance of the wooden structure. On the right side, firefighters can turn off gas power and pick up the adequate fire extinguishers.data.*

Evaluation and discussion

In order to analyze the difference in performances among the group trained by traditional manual instruction paper and the one trained on VR, an experiment is run: volunteers have to perform the operations they have been trained for. Then, a survey is used to evaluate our system. It measures participants' perceptions on VR usability.

22 participants were recruited for this study. All performed training and the trials. two of which had later to be excluded due to problems with 20 recordings. 6 female and 14 male, with age ranging from 25 to 31 years participated in the training without

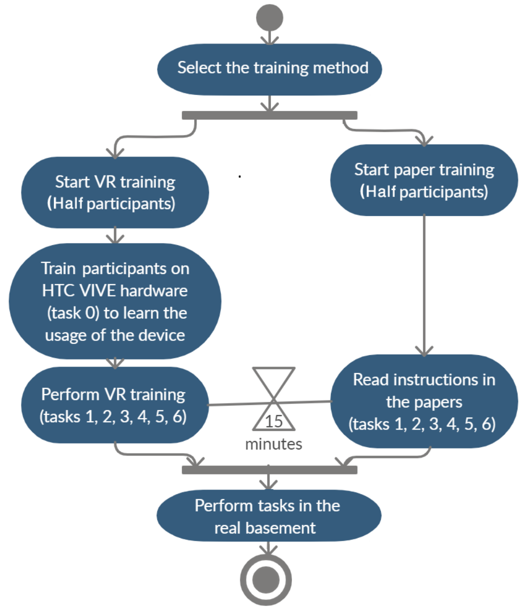

Figure 4. *Activity diagram of the training process.*

prior knowledge on how to use the HTC Vive device. During the experiment, none of participant reported severe motor, visual disabilities or disorders. All of them with visual impairments wore corrective glasses or lenses. The experiment was divided into two training and a test in the basement of the Italian firefighters rescue units (as presented in Figure 4). In the training room, the first group of trainees started the VR training while the second one read the paper instruction for 15 minutes. Besides, the first group was training on using the VR hardware which is HTC Vive in our experiment. After finishing the training, The trainees were taken to the real basement of the Italian firefighter building. Each trainee started the test and performed the tasks. At the end of the test, all participants were administered a system Usability Scale (SUS) questionnaire addressing six features: user-friendly, comfortable, clear content information, design, interaction, and easy to remember which were measured using a 5-step Likert scale reaching from “strongly disagree” to “strongly agree”. We included different questions about usability of participants and their motivation for using VR training. the mean values are calculated per question for measuring usability on the Likert scale by indicating the 95% confidence interval around the median for each usability metric (as shown in Table 2).

The results of the first fourth tasks based on VR training that depends on interaction of the participant with objects has 78% of task-completion rate while the fifth task of reading instructions for Gas suppression system did not reach the average task completion rate (as presented in Figure 5). This can be explained by the similarity of tasks based on interaction between the participant and objects in VR and in reality. However, during the sixth task that focuses more on clear information metrics and design features as the wooden structure, VR-based trained participants show greater results than paper-based trained one (more than 80% of task completion rate). Hence, our VR training achieves the effectiveness metric for usability. The data visualization tasks (5 and 6) took more time for VR-based trained participants. This can

Median ± Standard Deviation (SD) values per question for measuring usability and UX on Likertscale.

	Training	Median	SD
UX	VR	4.2	±0.6
	Paper instructions	2.8	±1.2
Satisfaction	VR	3.6	±1
	Paper instructions	3	±1.3
Efficiency	VR	3.2	±1
	Paper instructions	2.7	±1.2
Effectiveness	VR	3.5	±1.2
	Paper instructions	2.7	±1.4

be explained by the amount of information shown in these tasks. Therefore, in our VR training, the participants perform tasks (1, 2, and 3) faster than other tasks (as shown in Figure 6).

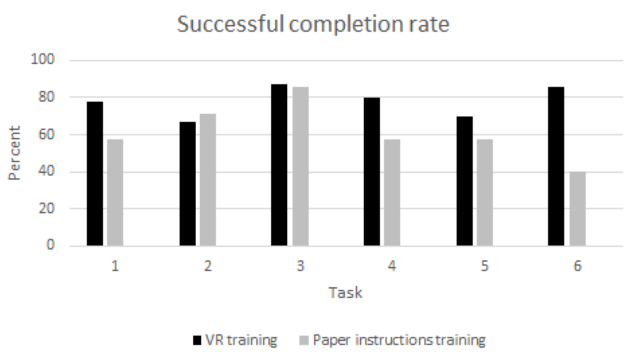

Figure 5. Effectiveness of the proposed training: percentage of successful completion rate per task.

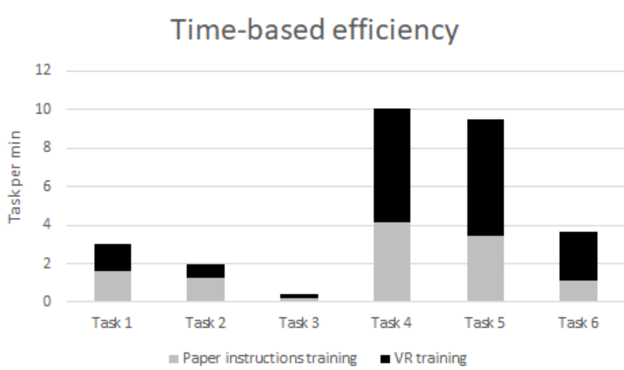

Figure 6. Time based effenciency per task.

The analysis of the questionnaire reveals some interesting differences between VR and paper for training. In the following, some open text comments are reported:

- I wish to try VR rather going with paper.
- The system was very well designed. I would avoid having long texts.
- I like the VR training and I felt that the design is realistic. I wanted to try it again.

These comments show that learning objectives have been met at least with respect to the subjects' self-reported learning. The long text such as in the fifth task makes the user of HMD feeling bored. The trainees were enjoying interacting with objects more than visualizing tasks. The last task is about verifying the wooden structure. The paper instructions' trainees could not accomplish this task and remember the design with an approximately 40% of task completion rate (as shown in Figure 6). However, most of the VR trainees could remember the wooden design even through playing the game without memorizing the tasks. Thus, our simulation can allow the brain of the trainees to memorize and carry out tasks naturally. During the initial design phases of the basement and objects, there were many concerns that the trainee would not be able to perform tasks cited by the firefighters' curators, would not find the button of the electrical power or the healing plant, and would not able to follow or remember neither the layout of the real basement because of the complex path nor the chain of tasks, and that the VR training for 15 minutes may not provide feedback on the usability and UX. All of these concerns proved to be false. The VR training did work quite well with trainees. Many of them used the VR hardware for the first time and was able to finish the VR training on HTC Vive hardware relatively quickly. Then, they were able to interact with objects and accomplish most of the tasks, especially those that depend on interaction (1, 2, 3, and 4). The training system was highly reliable, though our guideline for deploying two different training proved necessary. The sequence of predefined tasks was well-mentioned and highlighted in the VR training. Thus, most of the trainees of VR could remember the tasks through the shape of objects such as wooden structures and heating plants. Furthermore, well-maintained lighting levels increase trainees' mood and alertness. Thus, the trainees of VR were not surprised by the darkness in the basement and could easily recognise the location of their tasks. This research defines the impact of the use of VR on the activities carried out by users in emergency contexts such as an earthquake situation. In particular, this improves the situation awareness and the safety of the users operating in the field. Besides, it enhances the effectiveness of the operations carried out in operative control rooms. Furthermore, it grants a fast and effective response through a definition of new system operating procedures.

Conclusion

In this paper, the outcomes of a simulation-based firefighter training is presented. The game development has been conducted in close cooperation between Italian firefighters rescue units, researchers, and game developers. Based on this experience, we developed a model as a guideline for creating VR training for first responders. This model consists of a collection of requirements, contexts, and objectives. In our application scenario, an after-earthquake scenario was specified by the firefighters' curators (domain experts): a group of firefighters must enter a real basement under the building of the rescue units of the Italian firefighters after an earthquake and perform specific tasks. We have evaluated the developed training system in terms of usability. The results show that the use of VR improves the perception of the scene allowing trainees to perform a faster and less risky intervention.

Acknowledgments

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References

[1] Unity real-time development platform.

[2] S. Arnab, T. Lim, M. Carvalho, F. Bellotti, S. de Freitas, S. J.-J. Louchart, N. Suttie, R. Berta, and A. D. Gloria. Mapping learning and game mechanics for serious games analysis. *British Journal of Educational Technology*, 46(2):391–411, January 2014.

[3] A. Behzadi. Using augmented and virtual reality technology in the construction industry. *American Journal of Engineering Research*, 5(12), 2016.

[4] M. Cha, S. Han, J. Lee, and B. Choi. A virtual reality based fire training simulator integrated with fire dynamics data. *Fire Safety Journal*, 50:12–24, 2012.

[5] Z. Feng, V. González, R. Amor, R. Lovreglio, and G. Cabrera-Guerrero. Immersive virtual reality serious games for evacuation training and research: A systematic literature review. *Computers & Education*, 127:252–266, 2018.

[6] Z. Feng, V. A. González, V. Mutch, R. Amor, A. Rahouti, A. Baghouz, N. Li, and g. Cabrera-Guerrero. Towards a customizable immersive virtual reality serious game for earthquake emergency training. *Advanced Engineering Informatics*, 46:101134, 2020.

[7] I. Heldal and C. Wijkmark. Simulations and serious games for firefighter training: Users' perspective. In *ISCRAM*, 2017.

[8] W. Iso. 9241-11. ergonomic requirements for office work with visual display terminals (vdts). *The international organization for standardization*, 45(9), 1998.

[9] X. Li, W. Yi, H. Chi, X. Wang, and A. Chan. A critical review of virtual and augmented reality (vr/ar) applications in construction safety. *Automation in Construction*, 86:150 – 162, 2018.

[10] X. Lu, Z. Yang, Z. Xu, and C. Xiong. Scenario simulation of indoor post-earthquake fire rescue based on building information model and virtual reality. *Advances in Engineering Software*, 143:102792, 2020.

[11] J. Melzer and K. Moffit. Head-mounted displays. *Digital Avionics Handbook*, 2001.

[12] P. Monteiro, M. Melo, A. Valente, J. Vasconcelos-Raposo, and M. Bessa. Delivering critical stimuli for decision making in vr training: Evaluation study of a firefighter training scenario. *IEEE Transactions on Human-Machine Systems*, 2020.

[13] D. Oliva, B. Somerkoski, K. Tarkkanen, A. Lehto, and M. Luimula. Virtual reality as a communication tool for fire safety-experiences from the virpa project. In *GamiFIN*, pp. 241–252, 2019.

[14] P. Tregenza and D. Loe. The design of lighting, published by e&fn spon, 1998.