HCP–VR: Training First Responders through a Virtual Reality Application for Hydrogeological Risk Management

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Abstract: Training First Responders (FRs) can represent a difficult task due to the need for preparing trainees to face dangerous situations without exposing them to actual risks. VR technology can help overcome these limitations by offering accurate simulations in which trainees can safely experience critical scenarios while improving their knowledge and skills about a specific procedure. In this paper, a Virtual Reality Training System (VRTS) designed to train FRs in the High Capacity Pumping (HCP) procedure is presented. This application aims to prepare operators through two different training modes (Guided and Evaluated) within a realistic computer-generated scenario. A user study involving 22 operators from the Civil Protection of Regione Piemonte was conducted to assess the learning efficacy and the overall quality of the VRTS. Feedback was collected both via qualitative evaluations and a quiz session on theoretical content. Participants praised the usability of the application and the overall quality of the training experience. Finally, the scores of the quiz session showed a knowledge gain associated with the use of the VRTS to train in the considered procedure.

1 INTRODUCTION

When they need to take action, First Responders (FRs) are required to follow strict guidelines to secure their and others' safety, since they often work in life-threatening situations and operate tools and machines that can be dangerous in case of misuse. This observation is particularly true for operators that manage crises in the event of hydrogeological disasters, who often are called upon to act when the event is still ongoing and must use equipment with high pumping capacity that, if used carelessly, can cause victims among both operators and civilians. It is, therefore, necessary for FRs to undergo appropriate training that can prepare them to face high-risk situations.

However, training in the context of the High Capacity Pumping (HCP) module of Civil Protection can be difficult. On the one side, operators must be prepared to work in hostile conditions, whereas on the other side, it is not possible to expose trainees to actual risks. Training operators using theoretical lessons neglects the practical skills that are required during on-field operations. Engaging the trainees in practical exercises overcome this limitation, but presents a different set of problems. In particular, the equipment for these operations includes expensive pumps whose number is limited; if a pump is deployed for training, it cannot be readily available in case of an emergency. If the pump is deployed as a training device for a limited time, not all the trainees can operate it, leading to an incomplete training process. Moreover, even if the equipment is deployed for a sufficient amount of time, it must still be used in safe conditions to safeguard the trainees' health; therefore, the resulting training practice is just an approximation of a real scenario.

The restrictions above can be addressed by introducing a Virtual Reality (VR) module as a complement to the traditional HCP training, since VR technology can simulate high-risk scenarios without exposing the users to actual dangers, and in particular immersive VR applications can be used to acquire the practical skills associated to the considered procedure. In this paper, a VR application for training FRs is presented. This VR Training System (VRTS) simulates a realistic scenario where the trainees can follow all the steps of the HCP procedure and use the relative equipment (pump, tubes, hoses, etc.). The VRTS offers two different training modes: a Guided (or scaffolded) Mode to learn the different steps of the procedure, and an Evaluated Mode to assess the trainee's knowledge and practical skills.

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To evaluate the overall learning value, the attractiveness and the usability of the developed system, the application was tested with volunteers from Civil Protection, and feedback was collected (before and after the experience) and later analyzed.

The activity was performed in collaboration with an Italian regional Civil Protection body, involving in particular several Civil Protection and Forest Fire Fighting Units of Piedmont Region, Italy and the Piedmont Region Coordination body of Civil Protection Volunteering in the context of the PITEM RISK project (for which Politecnico di Torino has been appointed as the implementing body for the Piedmont Region). More specifically, this paper builds on a VR application developed for the RISK FOR sub-project, which aims at improving the training of the many actors involved in the disaster management of the ALCOTRA region, a territory between Italy and France. The presented activities, though, fall within the scope of the RISK ACT sub-project, whose goal is to exploit the outputs of RISK FOR in real-world use cases such as the one situated in the considered application.

2 RELATED WORKS

In the last years, the use of VRTSs has seen a great diffusion in many contexts including academia, medical field (Kaluschke et al., 2018), and industry (Pérez et al., 2019). VRTSs have been especially useful for training activities that are mainly focused on practical tasks involving specialized equipment. In such cases, training can be enhanced by learning experiences that offer hands-on approaches (Gavish et al., 2015). It was demonstrated that the use of VR in this type of learning contexts can be more beneficial with respect to the use of other types of training tools, such as printed material or video lessons. In particular, VRTS are more effective in terms of procedural knowledge retention and confidence when compared to printed learning tools (Buttussi and Chittaro, 2021), whereas they are more efficient in terms of retention of information and self-efficacy increment when compared to non-immersive, video-based trainings (Lovreglio et al., 2021). Another aspect that contribute to the diffusion of VRTSs is the fact that VR technology is particularly suited for the creation of training tools, mainly due to its ability to simulate (Lateef, 2010) real scenarios with a high level of accuracy and without exposing users to the corresponding risks. For example, it is possible to recreate an evacuation scenario in the event of a road tunnel fire (Calandra et al., 2021), where the users can learn emergency regulations while experiencing a realistic simulation of fire and smoke.

Based on the above considerations, VRTSs are particularly useful for the education of FRs or other operators that must train in practical tasks while working in dangerous situations. In facts, immersive VR applications have been largely adopted in risk-management contexts: for example, to train operators in the CBRN procedure (Lamberti et al., 2021), or crisis management teams (composed by policemen, firemen and doctors) in rescue missions (Conges et al., 2020).

An additional advantage offered by VRTSs is the possibility to enhance the training efficacy by including automatic guiding and evaluation modules: users can be trained and evaluated directly by the application, therefore the presence of a trainer is not necessary. Regarding the design of these modules, despite the diffusion of VRTSs there are no standard rules to follow during the development of a new application. Nevertheless, it still possible to find general guidelines the describes the best design practices in the literature (Feng et al., 2018). In particular, the most common solutions for training consist in scaffolding systems that guide the trainee step-by-step, either using audio or textual feedback (or a combination of both). This feedback can consist either of instructions that describe the next step of the training, or correction given to the trainee after each task. As for the assessment of the users' performance, the adopted solutions are either run-time error signaling or the use of a final report that can be consulted only at the end of the VR experience.

To conclude, the present activities build on a previously published research activity on the use of simulation-based VR as a mock-up tool for training experiences (Pratticò et al., 2021). In the above activity, a sandbox VR application was used to support Training Provisioners (TPs) in designing a training experience, and this approach was compared to a standard, dramaturgy-based one. In this paper, the feedback and the results collected from the TPs are used to improve that VR application and to implement a guiding and an evaluation system into it to safely train operators from Civil Protection.

3 METHODOLOGY

This paper presents a VR-based experience to train operators from Civil Protection in the HCP procedure. An existing, sandbox VR application was first improved accordingly to previously collected feedback from Civil Protection TPs, and later used to build a VRTS targeted to FRs.

3.1 HCP Module and Procedure

The HCP module is a part of the *Colonna Mobile*[1] of Civil Protection; it consists of a series of vehicles and teams of operators that must be dispatched in the event of a hydrogeological crisis. It is described by a series of general guidelines that define the tools and the overall procedure to guarantee the interoperability of modules from different countries (”Euratom”, 2008). The procedure consists of a series of steps that the FRs need to follow to operate high-capacity pumps, drain flooded areas and monitor water levels.

In particular, when a hydrogeological crisis occurs, the FRs must wear the necessary Personal Protective Equipment (PPE), then approach and inspect the deluged ground; this first phase aims to assess the situation and identify the area that must be drained (aspiration area, generally a puddle) and the delivery area (e.g., a river) where the water can be discharged. The operators must then place the pump near the aspiration area, in a feasible location for the pumping activities: the placement must consider the characteristics of the pump (capacity, power) and the environment (height, obstacles) since they all contribute to the success of the operation. In case of a wrong placement (e.g., too far from the aspiration area), the pump will fail to move the water.

Once the pump is correctly placed, the operators must delimit the operational field and start assembling the aspiration and delivery chains using rigid or semi-rigid tubes and, for the latter, also foldable hoses. The two chains must be connected to the pump and directed to the aspiration and delivery areas, respectively. The aspiration chain must end with a filter that shall be submerged in the flooded area. The operator that places the filter must wear additional PPE (a life vest secured with a safety rope) to limit the chances of drowning. The delivery chain must end with a rigid tube anchored to the ground near the delivery location. If the delivery area is another river, a protective sheet must be used to protect its bank.

Once the above steps have been completed, the operators can start the pumping procedure and wait for its completion. During this phase, they must monitor the pumping activities to assess the state of the aspiration and delivery chains and detect possible water leakings. If leaking is detected, the procedure must be stopped and the tubes repaired or substituted. The operations terminate when all the water is removed from the aspiration area.

[1]https://www.regione.piemonte.it/web/temi/protezione-civile-difesa-suolo-opere-pubbliche/protezione-civile/logistica/colonna-mobile-regionale

3.2 VR Application

The application was developed for immersive VR Head-Mounted Displays (HMDs) like Vive Pro[2] and Oculus Quest 2[3], and the bundled hand controllers were used to interact with the Virtual Environment (VE). The system was implemented using Unity[4], and the VR component was handled using the SteamVR framework. The 3D assets were created using Unity (for the VE), Blender[5] (for the tools, the pump, the vehicles, and the characters), and image-editing software (for the textures).The logic and algorithms controlling the virtual 3D objects were wirtten in the C# programming language.

The application was initially designed as a sandbox experience where the users can freely interact with the tools used in the HCP procedure. The VE was modeled as a realistic deluged area between two rivers, near a forest but easily accessible by vehicles (Fig. 1). The behavior of the equipment was based on the HCP guidelines, manuals, and empirical observations collected during Civil Protection real exercises. For instance, the pump was implemented to simulate all the necessary steps for the pumping procedure, using the instruction manual as a reference. The users can interact with all the doors and valves and start the pumping procedure by interacting with the control panel. Moreover, audio feedback was used to enhance realism and replicate the noise of the engine, and a particle effect was exploited to simulate the water ejected at the end of the delivery chain.

Figure 1: The fictional environment used in the VRTS. It is a realistic reconstruction of a deluged area between two rivers that can be accessed easily by vehicles.

Particular care was also dedicated to the simulation of the aspiration and delivery chains. Rigid tubes were implemented as single 3D objects; semi-rigid

[2]https://www.vive.com/us/product/vive-pro-starter-kit/
[3]https://www.oculus.com/quest-2/
[4]https://www.unity.com/
[5]https://www.blender.org/

tubes and foldable hoses were handled instead as couples of different 3D elements (the end-points) connected by a third element simulating the realistic behavior of the tube/hose itself. Regardless of the type and the implementation, all the tubes can be assembled to build the aspiration or delivery chains and can be connected directly to the pump.

Although the user can interact with every 3D element (with the help of visual cues highlighting the objects during the interaction), the experience can change depending on how it is configured. In particular, the user can choose a particular task (delimiting the operational field, assembly of the delivery or the aspiration chain, etc.) to activate only a subset of 3D objects. When the chosen task requires more than one operator, Non-Player Characters (NPCs) can help the user (e.g., to transport the tubes). The NPCs were implemented using an event-based approach and finite-state machines. Furthermore, voice-overs were added to the NPCs to give the general context to the users.

3.3 Improvements

As mentioned above, feedback collected during a previous study (Pratticò et al., 2021) was used to improve the usability and the realism of the existing application. In particular:

- two training modes were added to the application in order to train operators in the HCP procedure;
- the overall graphics quality of the VE was improved by substituting the tree models with new ones without billboarding effects;
- the behavior of the NPCs was modified to improve the realism; some of the animations were changed, and the parameters managing the inverse kinematics were tuned to obtain more accurate and esthetically-pleasing results;
- the user's hands (previously static models holding the 3D geometries of the HMD controllers) were substituted with animated hands to enhance the realism and the user's sense of immersion;
- the tubes' and hoses' logic was changed in order to improve the assembly interaction and the overall behavior (in particular the effect of gravity on the tubes' endpoints);
- the audio effect associated to the pump was changed and its intensity was linked to the pump's doors (closing a door reduces the volume);
- a multiplayer version of the VR application was developed to train multiple users at the same time; in this version, two operators can work together (Fig. 2) inside the same simulation to complete the procedure, helping each other in assembling the aspiration and delivery chains and in the management of the pump.

(a) (b)

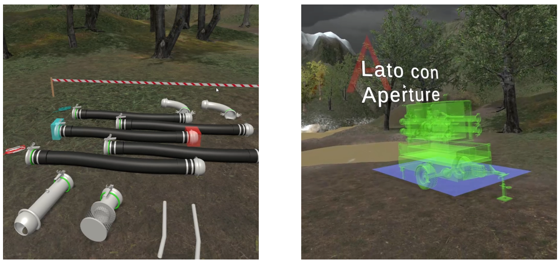
Figure 2: Two operators working together in the multiplayer version of the application: they meet and communicate at the beginning of the simulation (a), and assemble the delivery chain, connecting a semi-rigid tube to the pump (b).

3.4 Training Modes

The results obtained in the previous study (Pratticò et al., 2021) were used to design and add two different training modes to the existing sandbox application: a Guided Mode (GM) and an Evaluated Mode (EM). In particular, feedback from the TPs was used to define:

- the correct order of operations to complete the procedure;
- the guidelines to ensure the operators' safety;
- the theoretical content to be delivered during the training.

The main goal of the GM is to instruct the trainees to complete the HCP procedure, focusing not only on the order of the operations but also on the reason behind each action. In this mode, the whole procedure is divided into micro-tasks (e.g., "take the protective sheet and place it"), and the trainee is guided through them by a scaffolding system using voice-overs, highlights and icons (Fig. 3). The voice-over is diegetic, and it is inserted in the scene as a radio communication from the leader of the operators. For each micro-task, the voice-over describes the necessary actions to complete it, while the highlights point out all the elements mentioned by the voice-over. If the trainee successfully complete the micro-task, the voice-over describes the next step and the procedure continues. If the trainee fails (e.g., he or she makes a mistake), the voice-over signals the error and describes a possible correction. At any moment, it is possible to repeat the last instruction described by the voice-over by pressing a button on the hand controllers. The GM ends when the trainee successfully complete the last micro-task. Similarly to the original sandbox application, it is possible to be guided through the whole procedure or through a subset of micro-tasks (e.g., only the assembly of the delivery chain).



(a) (b)

Figure 3: Highlights and icons used in the GM to guide the trainees in the HCP procedure. In (a), the blue and red highlights point out the endpoints of a semi-rigid tube to explain how to assemble the aspiration chain; in (b), the highlights describe where to place the pump.

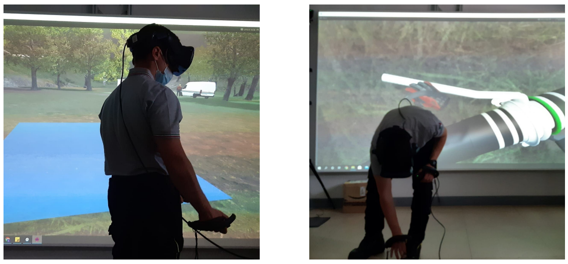
In the EM, there is no guiding system and the trainee is free to interact with all the 3D objects. Mistakes are not signaled (the only feedback is the behavior of the pump and the other objects in the scene), but the trainee can undo the actions performed previously and correct errors (if he or she notices them). An evaluation module keeps track of the trainee's actions and produces a report at the end of the simulation. This report aims to highlight incorrect actions (e.g., "You forgot to wear the PPE") and give an overall evaluation on the user's performance. This training mode is designed to be used multiple times to gradually improve the user's performance until no error is made.

4 EXPERIMENTS

In order to assess the overall quality of the developed VRTS (learning effectiveness, potential as a learning tool, usability, attractiveness), a user study was conducted with 22 subjects from the Civil Protection of Piedmont Region. The participants came from different cities – therefore, from different Civil Protection sites/units – and their knowledge of the HCP procedure varied (some participants were unfamiliar with the procedure, other claimed to have previous knowledge on the topic). None of the subjects had previous experience with immersive VR applications. The age ranged from 30 to 73 years ($\mu = 55.38$, $\sigma = 9.69$).

4.1 User Study

In the user study, the participants were asked to fill in a questionnaire and take a quiz on the HCP procedure to collect background information and assess previous knowledge of the procedure. Afterwards, each subject was asked to experience the VRTS in GM to train in the HCP procedure, and was also offered the possibility to use the EM to get a a feedback on the performance (Fig. 4). All the experiments were conducted using the single player version of the VRTS. Finally, the subjects were asked to take the same quiz used before the experience to assess the knowledge gain associated with the use of the VRTS, as well as to fill in a second part of the questionnaire evaluating the whole experience and collecting general feedback and possible suggestions for future improvements.



(a) (b)

Figure 4: An operator from Civil Protection using the VRTS. In (a), the operator is placing the pump; in (b), the operator is assembling the aspiration chain.

The quiz used in this study consisted in a series of multiple-choice questions and one open-ended question. The multiple-choice questions concerned procedural details like:

- where to place the pump;
- how to use the PPE;
- how to operate the pump's valves;
- how to operate the pump during the pumping procedure;
- how to secure the operational field;
- how to assemble the delivery and aspiration chains.

The open-ended question, instead, concerned the whole procedure and asked to briefly describe the final goal of the HCP module.

The questionnaire administrated to the participants was composed of several sections to investigate different aspect of the training experience and the developed VRTS. In particular:

- the first section encompassed general questions on the participant's background (experience with Civil Protection, with the HCP procedure, and with immersive VR applications or video-games);
- the second section consisted of the Instructional Materials Motivation Survey (Keller, 2010), or IMMS. This section is composed of 36 statements

to be scored on a 1-to-5 scale (with one corresponding to “not true” and five to “very true”) to evaluate the participant’s motivations at learning the HCP procedure. The statements considered in this section can be grouped in four categories (attention, confidence, relevance, and satisfaction) and their scores can be used to get an evaluation for each category.

- the third section consisted of a subset of the AttrakDiff questionnaire (Hassenzahl et al., 2008) to evaluate the Attractiveness (ATT) and Hedonic Quality Stimulation (HQ-S) of the experience (Jost et al., 2020). In particular, this section evaluated the training experience using 14 pairs of terms to which the participants were asked to assign a value on a 1-to-7 scale.
- the fourth section aimed to evaluate the general usability of the VRTS and was based on the System Usability Scale (SUS) (Brooke, 1996). It consisted of 10 statements to be scored on a 1-to-5 scale (with one corresponding to “total disagreement” and five to “total agreement”).
- finally, the fifth section encompassed general questions on the whole training experience, the behavior of the NPCs, and the satisfaction and confidence of the participant.

4.2 Results

The collected results were used to evaluate the training experience. In particular, the questionnaire was used to get a subjective estimation of the characteristics of the training and the developed VRTS, whereas the quiz session provided an objective evaluation of the knowledge gain. There were no significant differences between subjects with previous knowledge of the HCP procedure and subjects with no experience on the topic.

Starting with the subjective evaluation, the results on motivations at learning (IMMS) are reported in Fig. 5. As it can be seen, the training experience managed to hold the trainees’ attention during the study and was considered as satisfying. The participants judged the experience as relevant, and considering the total score they were motivated to complete the training. Looking at the individual answers of the IMMS questionnaire, the attractiveness of the tackled topic (the HCP procedure) and the quality of the information provided by the VRTS helped the trainees to remain focused during the experience, hence the high score assigned to the attention category. Regarding the relevance category, its score can be linked to the usefulness of the topic, together with the fidelity of the simulation and the organization of virtual training. Finally, considering the confidence category, even though the trainees were overall confident about their knowledge at the end of the experience and praised the organization of the provided content, they pointed out that at, the beginning, they were unsure about the effectiveness of a VR training, hence the lower score.

Figure 5: Results collected through the IMMS questionnaire; the plot reports the results for each of the grouped category (attention, satisfaction, relevance, confidence, total) as well as the total score.

As for the results of the AttrakDiff questionnaire, they are showed in Fig. 6. The training received low scores for each pair of terms proposed by the questionnaire, which means that the experience was judged to be positive both in terms of attractiveness and hedonic quality stimulation. In particular, it was praised for being innovative and for the novelty of the chosen approach, whereas the higher score assigned to the “bold/cautious” and the “challenging/undemanding” pairs are probably linked to the fact that the structure of the training experience was similar to that of “standard” (non-VR) HCP training.

Moreover, the developed VRTS was tested using the SUS questionnaire, and the results showed that the usability was judged to be good ($\mu = 75.95$, $\sigma = 12.96$) overall. The participants praised the functionality offered by the system, though some of them weren’t sure if they could use the application without a technician’s support (this outcome could be due by the fact that the subjects had no previous experience with VR applications or video-games).

Finally, regarding the objective evaluation, the results collected in the quiz session are given in Fig. 7. The multiple-choice questions were marked on a 0-to-6 scale, with one point assigned to each procedural detail being investigated. Considering the score obtained before and after the experience, a significative increment was observed (3.13 before vs 4.04 after, $p = 0.02$), indicating a knowledge gain associated to

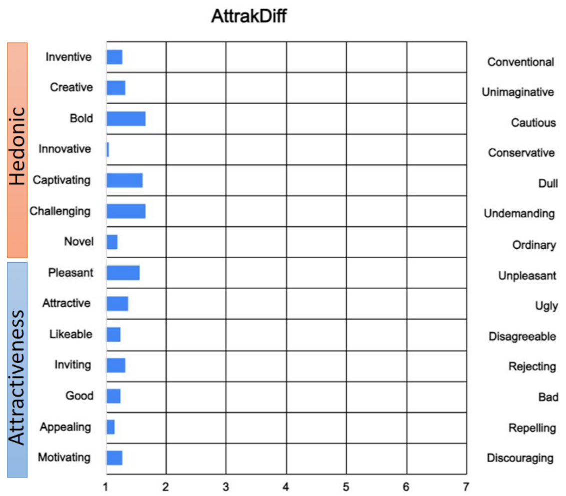


Figure 6: Results collected through the AttrakDiff questionnaire.

the training experience. The open-ended question was not scored, but it was observed that after the training the participants were able to describe the HCP procedure and the aim of the HCP module with higher accuracy.

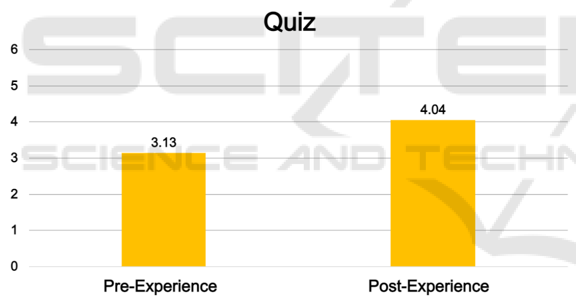


Figure 7: Results of the quiz session: the left column refers to the questions administered before the training experience, whereas the right column summarizes the post-experience ouctomes.

5 CONCLUSIONS

This paper presented a VRTS developed as a follow-up to a previous study and designed as a tool for training FRs in the HCP procedure. The application was developed to overcome the limitations of the standard training. In facts, VR technology can offer detailed and accurate simulations of potentially life-threatening scenarios where users can train without incurring in actual risks. In particular, the developed application simulated a scenario where FRs must act in the event of an hydrogeological crisis: using a high-capacity pump, the operators must drain a deluged area while respecting all the safety regulations. The VRTS offered two different training modes to train in the procedure and assess the trainees' knowledge.

To assess the VRTS, a user study was conducted. Operators from Civil Protection were asked to experience the application, and questionnaires were used together with theoretical quizzes to evaluate the overall quality and the efficacy of the developed training tool. The results showed that the participants appreciated the training experience in terms of usability, attractiveness and hedonic quality. They showed also that the participants were able to maintain a high level of attention, and that the learning experience was considered to be satisfying and relevant. Finally, the objective results collected with the quizzes showed a significative learning gain associated to the learning experience, regardless of trainees' previous knowledge on the subject matter (the HCP procedure).

The study also highlighted some limitations. In particular, a participant pointed out the necessity to use this VRTS as a complementary module to the standard training (which is the currently intended use), and not in substitution, citing the differences between the 3D objects and the real, heavy equipment as one of the reasons. Other limitations concerned the fact that, at this moment, it is possible to train in only one virtual scenario, and the overall dullness of the NPCs.

Possible future developments include overcoming the above limitations. In particular, a possibility could be to add different scenarios with different characteristics (an urban one, or one with different height levels) to the VRTS. Another extension could concern improving the NPCs' behavior by adding the possibility to control them using the voice to enhance the overall realism of the experience. Finally, a possible extension to this study could consist in using the multiplayer mode to train operators and analyze the impact of collaboration on the effectiveness of the training.

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