A Multi-role, Multi-user, Multi-technology Virtual Reality-based Road Tunnel Fire Simulator for Training Purposes

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Abstract: The simulation of fire emergency scenarios in Virtual Reality (VR) for training purposes has a large number of advantages. A key benefit is the possibility to minimize the associated risks if compared with live fire training. Fire in road tunnels is among the most complex and hazardous events to be dealt with in this context, since the outcome of the incident depends on the actions of both the emergency operators and the involved civilians. This paper presents a VR-based road tunnel fire simulator designed to support multiple roles (firefighters, as well as occupants of both light and heavy vehicles) which can be played by multiple networked users leveraging a broad set of technologies and devices. The simulation tool – named FrèjusVR – is developed as a serious game for training purposes, and includes functionalities to assess the users' actions which make it suited to a broad range of applications encompassing not only the training of operators, but also the study of human behavior during emergencies and the communication of safety prescriptions to tunnel users. The simulation uses data from a Fire Dynamics Simulator (FDS) to support a realistic visualization of smoke in VR, whereas for reproducing the spreading of fire a non-physically accurate, yet credible, simulation is adopted in order to guarantee interactivity.

1 INTRODUCTION

The use of Virtual Reality (VR) technology for training purposes is definitely not new. VR allows the creation of wide and complex Virtual Environments (VEs), enabling training situations that would be potentially hazardous or very resource-intensive if recreated for real (Engelbrecht et al., 2019).

Numerous works investigated the contribution of VR in the creation of effective emergency scenarios for training purposes (Andrade et al., 2018; Lu et al., 2020). Fire simulation is one of the most explored use cases (Fathima S J and Aroma, 2019; Corelli et al., 2020), due to the the number of possible hazards associated with live-fire training, in which firefighters are taught how to safely fight fires in a controlled and supervised setting (Engelbrecht et al., 2019). Fire simulation scenarios may have different aims. Firstly, they can be used as training tools for professionals; firefighters, in particular, could be prepared – both physically and mentally – for real life incidents (Engelbrecht et al., 2019). Civilians can be trained too, by showing them the correct safety behaviours. Secondly, they can be used for human behaviour investigations. For example, VR simulations can be used to study the reaction of civilians during the emergency (Kinateder et al., 2014b). Furthermore, they can be used for designing and studying the effectiveness of safety measures in a given scenario.

A particular class of fires, namely tunnel fires, are the most critical event type for users' safety (Ntzeremes and Kirytopoulos, 2019). When a fire develops inside a confined space such as a road or railway tunnel and involves heavy vehicles such as trucks, it can rapidly grow up and become completely uncontrollable. Hence, the prompt response of the fire officers is essential for evacuating involved peo-

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ple and then attacking the triggering fire. At the same time, the conformity of civilian users' behaviors to the emergency prescriptions plays a fundamental role in the incident evolution, since evacuation behaviours also have a social influence (Kinateder et al., 2014a) and can dramatically affect emergency operations.

An effective way to represent and manage the complexity of such situations is opting for a multi-user experience, e.g., by introducing virtual characters in the simulation (Engelbrecht et al., 2019). Alternatively, multi-user networked VEs provide a wide range of training and operation support possibilities. Multiple human users can visualize and interact with a shared scenario, practicing teamwork at a geographical scale (Louka and Balducelli, 2001). A weakness of this type of VR experiences is the lack of multi-user fidelity, if compared with solitary VR simulations (Engelbrecht et al., 2019). For example, in case of low visibility due to the presence of smoke, a firefighting crew would hugely rely on the sense of touch, which cannot be easily recreated with the commonly available haptic devices. Furthermore, if the visual representation of the other human users does not reach an proper level of credibility, factors such as immersion and perceived realism would be severely affected too. However, the evolution of commercial VR technology constantly leads to new systems, devices and functionalities. If correctly integrated, these elements may help to mitigate the mentioned issue.

The aim of this paper is to present a tool for multi-role, multi-user, and multi-technology VR fire simulation set in a road tunnel during a fire event. Multi-role refers to the possibility to impersonate either an emergency operator (i.e., a firefighter) or a non-professional user, being it a frequent user (truck driver) or an infrequent visitor (a civilian). Each of these roles has its own procedures to follow in an emergency, which are subjected to an assessment through the devised tool. This feature gives the simulation a threefold purpose: that of a training tool for firefighters, of a training tool to teach civilians safety behaviours, and of an investigation tool to study the civilians' behaviour during the emergency. Multi-user refers to the possibility, for different users in different places, to play the available roles all together and at the same time in a shared experience. As a matter of example, a firefighter trainee may play the operator role, while other users may be playing as civilians. Finally, multi-technology refers to the characteristic of the scenario of being designed to support a broad variety of VR device and system configurations, either common (desktop VR, HMD and controllers, etc.) or less widespread (like locomotion treadmills, leg sensors and motion capture suits). The

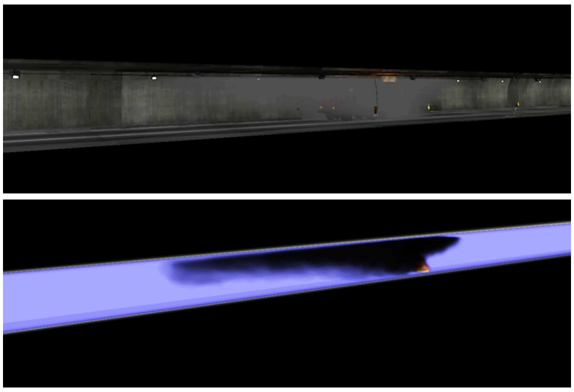

Figure 1: Smoke simulation displayed inside the VR scenario (top) and inside Smokeview, a tool for FDS visualization (bottom).

goal is to increase the effectiveness of the VR experience when beneficial hardware is available, while preserving the compatibility with common VR systems to prevent a strict technology barrier. In order to accurately represent the physical phenomena of gasses spreading inside the tunnel and further enhance experience fidelity, data of a Fire Dynamics Simulator[1] (FDS) were used to drive the visual representation of the smoke evolution (Figure 1).

The scenario, labeled FrèjusVR, was developed in collaboration with SITAF S.p.A.[2], the Authority of the Frèjus tunnel. Falling within the context of the PITEM RISK FOR[3] project, the serious game accurately reproduces a section of the real road tunnel, around the border between Italy and France, since the goal is to support the interoperability of procedures for fire management across the two countries.

2 BACKGROUND

To date, the use of VR to create simulations of emergency situations has been extensively investigated (Louka and Balducelli, 2001; Kinateder et al., 2014b; Lovreglio, 2020). The same can be said for simulations involving fire events, being them intended either for training or human behaviour analysis.

In (St Julien and Shaw, 2003), for instance, a firefighter command training VE in non-immersive VR was presented. The system, intended to instruct commanding officer trainees, allows the user to navigate the VE, visualize a building on fire from any angle, and command a squad of computer-controlled virtual firefighters. The correct sequence of commands leads

[1]https://pages.nist.gov/fds-smv/
[2]https://www.sitaf.it/
[3]https://www.pitem-risk.eu/progetti/risk-for

to the extinguishing of the fire with the lowest amount of danger to the squad. The system combines the representation of animated firefighters with the integration of a reasonable – but not physically accurate – fire and smoke simulation.

In (Ren et al., 2008), a VR system simulating emergency evacuations during fire was introduced. To increase the level of fidelity of fire and smoke, these phenomena were modeled by taking advantage of numerical fire simulations. Then, particle systems were used to visually represent them in the interactive VE. The aim was to show which evacuation techniques could be effective for building safety evacuation.

In (Cha et al., 2012), a real-time processing framework to develop fire training simulators based on FDS data was proposed, along with a set of data conversion techniques for the purpose. In this way, many useful physical quantities like toxic gases, heat, smoke and flames may be used both to visualize the results of the simulation and to measure safety achievements levels in the areas where the trainees pass through. The proposed framework was used to implement a single-user VR road tunnel fire simulator supporting simple firefighting actions such as evacuation and rescue. Inside the scenario, a safety level-based visualization mapping is used to display risk factors that are invisible but closely related with the safety of the trainees, such as toxic gasses and temperature distribution.

In (Xu et al., 2014), the FDS data were again used to drive the visual representation of a fire event. In this case, the purpose was to model and volumetrically visualize the smoke spreading inside buildings, with the aim to allow trainees to experience a realistic, but not threatening, fire scenario. An assessment model of the smoke hazard was also developed, in order to evaluate the safety of each different path for evacuation or rescue in virtual training.

In (Kinateder et al., 2013), a tunnel fire simulation for fire safety behaviour training was presented. The study, introducing the use of an immersive VR system (i.e., a CAVE), investigated the effect of information provided with or without VR on self-evacuation behaviors during the depicted emergency.

Interestingly, as shown in (Lovreglio, 2020), despite the tunnel fire scenario was largely explored in the past, the number of works that focused on training is very scarce, and mostly limited to fire safety behaviour training. A larger number of works pertained human behaviour investigations. However, most of them did not rely on immersive VR, or did not take advantage of the more recent HMD-based immersive VR systems. Finally, none of them was designed as multi-user experience.

3 SYSTEM DESIGN

In this section, the design of the proposed tool is reported, discussing the rationale for choices made.

3.1 Use Case

As mentioned in Section 1, this work has been developed in collaboration with the Fréjus tunnel Authority. A preliminary investigation was performed in order to identify the most representative use case for a road tunnel fire scenario. A smouldering fire developing from a light vehicle can be easily managed by the vehicle occupant, using one of the many extinguishers available along the tunnel. The same does not apply when fire originates from a heavy vehicle. Once the fire spreads to a flammable load, the situation can dramatically change, as demonstrated by all the severe fire events happened to date in road tunnels around the world, like the Mont Blanc in 1999 (BBC News, 1999), the Saint Gotthard in 2001 (BBC News, 2001) and the Fréjus itself in 2005 (BBC News, 2005). The tunnel depicted in the simulation is detailedly inspired to the real Fréjus tunnel, in particular to the one kilometer-long section over the Italy-France border; the represented fire event shares a number of similarities with the 2005 incident, such as the location and the initial conditions. The section layout and its apparatuses are shown in Figure 2.

At the beginning of the simulation, a car is travelling from Italy to France with two occupants onboard. At the same time, on the opposite lane, a truck is driving from France towards Italy. Suddenly, the engine truck catches fire and the heavy vehicle stops. Inside the car, which is traveling at 70 km/h, the radio reproduces status messages about the tunnel. Shortly before the car occupants can gain visual contact on the vehicle on fire, an emergency message is transmitted by the radio. At the same time, a unit of two firefighters (stationing in a fixed rescue place inside the tunnel) gets on a fire truck and starts driving towards the incident; at present, a vehicle belonging to the Italian National Fire Corps has been considered, though for the purpose of the said interoperability, a vehicle managed by Sapeurs-pompiers de la Savoie (SDIS 73) could be easily integrated. From this point on, actions of all the involved participants will affect the outcome of the whole simulation.

3.2 Roles and Procedures

In the above contexts, five roles can be identified. The car driver, the car passenger, the truck driver, and the unit of two firefighters. The car and truck occupants,

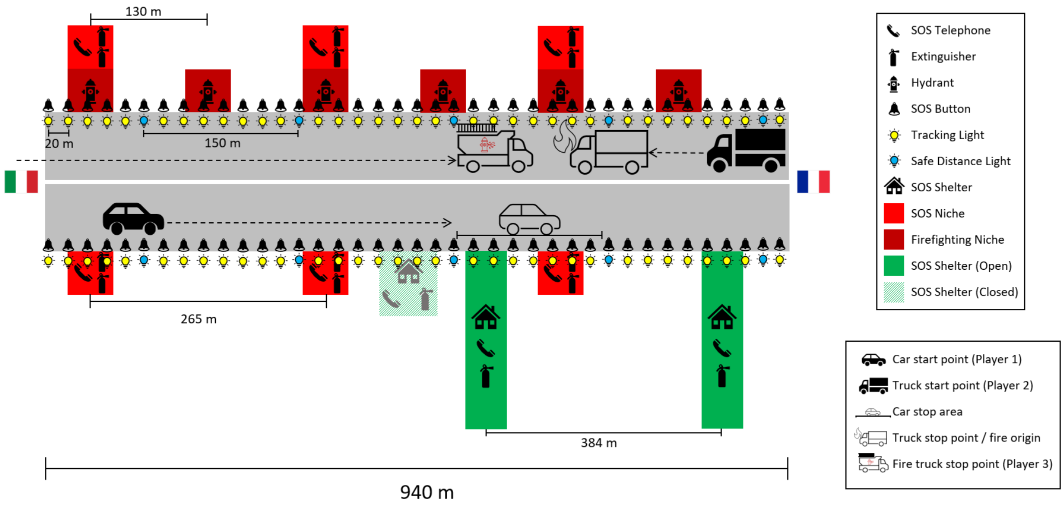

Figure 2: Layout of the simulated tunnel section.

in case of fire, have to follow the information printed on a double-sided safety brochure that is ordinarily handed over at the tunnel entrance. The green side of the brochure refers to normal conditions, whereas the red side (emergency) invites the user to:

- stop the vehicle, keeping a minimum distance of 100m from the burning vehicle (distances can be estimated by using the tracking lights inside the tunnel as reference: a blue pair is placed every 150m, interspersed with yellow pairs every 20m);
- turn off the engine and enable the hazard lights;
- reach the nearest shelter following the indications;
- if possible, ask for help by using the SOS telephone in a niche or pressing a SOS button;
- if willing to do that, use the extinguishers available in niches and shelters.

The truck driver is provided with a fire extinguisher under the truck driving seat.

In the meantime, the firefighter unit has to follow its own procedure. In case of fire and smoke hazard, the firefighting unit stationing inside the closest fixed rescue place is the first to reach the incident site. Once the driver of the fire truck reaches the distance of 50m from the fire, the two unit components get off the vehicle and have to perform the following steps:

- verify the safety of the area, excluding the presence of threats;
- rescue possible victims, helping whoever is unable to move; in case of seriously injured victims, bring them out of the tunnel; help the other civilians to reach a safe place (i.e., a shelter or the fire truck);
- start attacking the fire once all the civilians are safe; the driver connects the back of the fire truck with the closest hydrant by means of a first hose; the other component grabs a second hose, connected to the fire truck and equipped with an handline nozzle, gets close to the truck and attacks the base of the fire with a mixture of water and foam;
- evacuate the area if the fire is not extinguished in the first few minutes.

In the simulation, the car passenger is intentionally made unable to move, stuck in the car due to a blocked seat-belt. The firefighting unit will have to free the civilian by cutting the seat-belt with ad-hoc scissors.

Although each of the above roles could be, in principle, played by a human, it has been noted that some of them would be characterized by a very limited set of actions to perform. Thus, the car passenger and the second firefighter (the driver) were designed as Non-Player Characters (NPC) only.

The assessment of each role had to take into account the set of available actions for each role, which can be mandatory or optional.

3.3 Fire and Smoke

Fire and smoke were managed separately. On the one hand, fire had to be handled in real-time, in order to guarantee interactivity with the firefighting unit. Thus, an accurate physical modeling was excluded.

Starting from the truck engine, the fire gradually has to spread to the other parts of the truck, and, in few minutes, to the whole vehicle. Before reaching this point, the firefighting unit should be able to properly attach it, by aiming the stream of water at its base. The civilian use of fire extinguishers, as well as the incorrect use of the fire hose (e.g., by aiming at the top of the fire) should not be considered enough for a complete extinguishing, but useful to slow down the fire evolution. Heat was also taken into account, not only for the spreading phenomenon, but also as a threat to the tunnel occupants.

Smoke, on the other hand, was designed with a completely different approach. Initial tests with common real-time particle systems showed a number of critical problems. Firstly, they required a dramatically high amount of particles to completely fill the tunnel. Secondly, the resulting visual effect and its evolution over time resulted to be not accurate enough for a fire-fighting training scenario. Hence, it was decided to drop the real-time constraint, and opt for a physically accurate smoke simulation, that will be detailed in the following section. Along with the effect on the users' visibility, the smoke had to be a source of intoxication for tunnel occupants without breathing apparatuses, eventually leading to a failure for the given user.

4 IMPLEMENTATION

This section illustrates the system implementation, along with the set of supported VR technologies. The architecture of the system is depicted in Figure 3.

4.1 Devices and Technologies

The scenario was developed in Unity as a SteamVR application. This choice guaranteed compatibility with a very large set of commercial VR systems, such as the HTC Vive, Samsung Odyssey and Oculus Rift, etc. However, in case of no HMD detected, the application falls back to non-immersive VR.

On the one side, for moving around in the scenario in non-immersive VR, a traditional mouse and keyboard approach was adopted. Locomotion in VR, on the other side, required a preliminary investigation. "Magic" techniques like teleporting were not considered, in order to guarantee a high level of immersion (Cannavò et al., 2020), whereas joystick-based movements showed to induce a significant cyber-sickness. Hence, it was decided to focus on more natural locomotion paradigms.

The first technique to be integrated was be the Arm-Swinging (AS), in which the user holds a button (the grip) and swings the hand controllers back and forth to generate virtual motion. In addition, the support for two locomotion treadmills was added, namely, the Cyberith Virtualizer (CV) (Cakmak and Hager, 2014) and the KATVR KatWalk[4] (KW). With these devices, the user slides his or her feet on a slippery surface to move in the VE. Finally, with the HTC Vive, two additional tracking elements (the Vive Trackers) can be attached to the user's legs to enable the Walking-In-Place (WIP) locomotion, in which motion is generated by marching in place. All these techniques were also evaluated with a preliminary single-user and single-role (civilian) version of the proposed system, considering aspects like usability, sense of immersion, presence, and sickness. In particular, in (Calandra et al., 2018), two techniques were considered: AS and CV, showing the superiority of the former. Then, in (Calandra et al., 2019), a further evaluation involved AS, KW and WIP. Results showed that AS outperformed both the other techniques, and the WIP was positioned in the middle.

The support for the Xsens MVN[5] motion capture suit was also integrated to enable full-body tracking and completely control the virtual representation of the tracked user on the other remote users' clients.

Finally, the combined use of a backpack PC and an inside-out VR system, such as the Samsung Odyssey, was exploited to implement a free-walk locomotion technique, untied from any external sensor, tracking area or wire. The only drawback of this technique is the need of a large walking area, comparable with that of the simulated tunnel section.

The support for CAVEs in combination with either affordable (Celozzi et al., 2010) or high-end 6DOF tracking techniques (like, e.g., motion capture systems by OptiTrack[6] or Vicon[7]) was initially considered. However, due to the substantially different interaction paradigms required in these environments w.r.t. those used by the already selected technologies, this option was later discarded.

The combined use of some of the mentioned configurations within a multi-user session can be seen in Figure 4.

4.2 Multi-user

For the networking, a slightly modified version of the Unity legacy high-level network API (U-NET) was used. A client-server approach was adopted, in which the server could be either hosted on a client or on a dedicated machine. In the second case, the server application provides a "control room" mode, in which the simulation can be visualized through a number of

[4]https://www.kat-vr.com/products/kat-walk-vr-treadmill

[5]https://www.xsens.com/motion-capture

[6]https://optitrack.com/

[7]https://www.vicon.com/

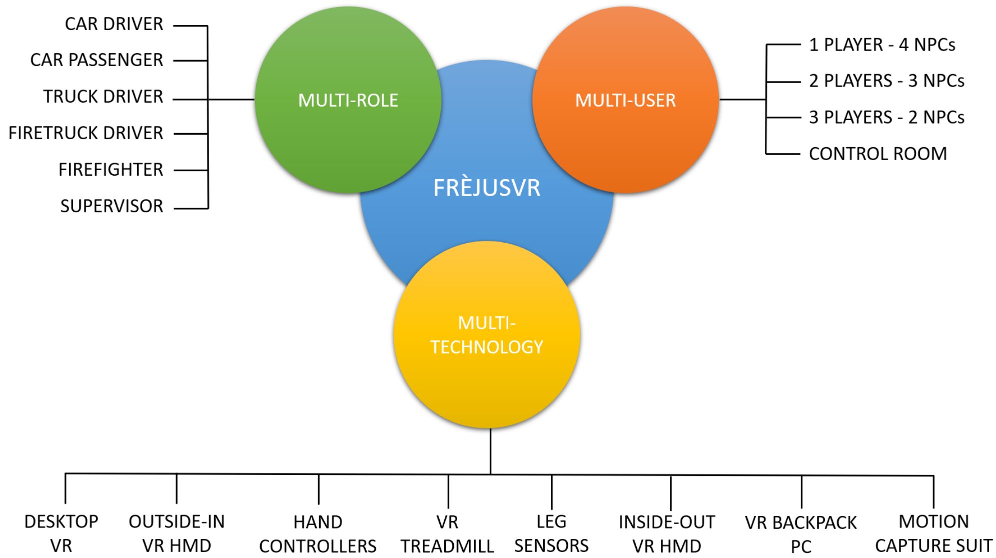

Figure 3: Architecture of the FrèjusVR system.

fixed security cameras placed along the tunnel. In this mode, a "director" user can modify the simulation, e.g., by speeding up or slowing down the fire evolution, turning off the tunnel lights, etc. Communications among users in the tunnel is guaranteed by a VOIP channel with 3D positional audio playback.

For the management of NPCs, the Unity built-in API (NavMesh) was used. A set of animations for each role was recorded with an OptiTrack system (in particular, for the firefighters), in order to maintain a high level of fidelity when the relative character is computer-controlled. Other animations which did not require a particularly high fidelity level were created in Blender[8], using also the add-on presented in (Cannavò et al., 2019) for speeding up the process.

4.3 Interaction with the VE

The interaction with objects in the VE is managed in a standard way. It is based on contact between the interactive object and the VR hand controller. The trigger button is used to initiate the interaction; in case of objects that can be grabbed, the user does not need to keep it pressed (a further click will drop the object). Extinguishers, once grabbed, require a further interaction with the other hand to take the safety off; then, the content can be sprayed by pressing a second button (the pad). The handline nozzle of the fire hose has to be managed with two hands, in order to simulate the real-life mode of operation (one hand to grab it, the other one to regulate the jet). Interaction with large and small doors will trigger an opening animation; for the shelters, doors will automatically close shortly thereafter. SOS telephones inside niches can be used to simulate a call with a safety operator; bringing the handset to the ear is enough to consider the relative action (help requested) as correctly performed. SOS buttons along the tunnel do not provide any feedback to the user because, as in the real setting, they just signal an issue at a given location.

At the beginning of the VR experience, users are let into a play-test room resembling the emergency shelter they will have to reach later during the simulation. In this VE they can freely familiarize with the locomotion technique, to visualize the safety brochure, and to try out some of the available interactions (in particular, the extinguisher and the SOS button).

Then, the simulation starts, and all the civilian users have their locomotion technique disabled, as they are travelling inside a vehicle in opposite directions. Vehicles autonomously accelerate up to 60 km/h, and maintain this speed unless the relative driver presses any controller button. This interaction will trigger the brakes, which is the only available action when vehicles are travelling. Shortly, the heavy vehicle will rapidly lose speed as the engine goes on fire. The car driver will instead travel inside the tunnel for few moments, until the truck on fire becomes visible. From this moment on, brakes will need to be activated in order to stop the vehicle at least 100m from the fire with the help of the blue tracking lights. If the brakes are not used, the vehicle will stop autonomously close to the truck. In order to increase the sense of immersion, during this initial part of the experience inside vehicles, users may be seated on a chair. However, the chair should be promptly re-

[8]https://www.blender.org/

Figure 4: Combined use of different devices and technologies in a multi-user FrèjusVR session. On the left: User 1, playing as a firefighter, equipped with an inside-out VR HMD, a backpack PC and a motion capture suit. On the top right: Point-Of-View (POV) of User 1, viewing User 2 and User 3. On the right: User 2, playing as a car driver, equipped with an outside-in VR HMD. In the center: POV of User 2, viewing User 1. User 3 playing as a truck driver from a desktop PC (not shown).

moved from the play-area as soon as user stands up after exiting the vehicle. In case of treadmills that support the seated position, the chair is not needed.

While in the vehicles, civilians will be allowed to interact with the cockpit (to turn off the engine, or to enable the hazard lights) and the door (to leave them). After having interacted with the door handle, they will found themselves in the tunnel, outside the vehicle. From now on, the locomotion techniques will be enabled, and users will be able to freely walk around, read the safety indications inside the tunnel, and follow the safety brochure. The brochure can always be displayed by using a controller button (the pad) if no objects are being grabbed with the relative hand.

The human-controlled firefighter, on the other hand, is kept inside the play-test room until the tunnel goes on emergency state. Then, the fire truck enters the tunnel and stops at 50m from the truck on fire. At this point, an emergency siren is activated, and the firefighter is instantly moved near the fire truck along with the NPC partner. Among the available interactions, the firefighter can open the car door, get the scissors from the partner, use them to cut the seatbelt and free the civilian, grab the fire hose, put it on ground closer to the fire, grab the handline nozzle, and use it to spray the vehicle on fire. Most of the discussed interactions are illustrated in Figure 5.

4.4 Fire and Smoke

As said, fire was modeled with a non-physically accurate, but credible, logic. The truck was split in various parts (engine, doors, wheels, tarpaulin, etc.), and each of them can burn differently and separately, controlled by parameters like ignition temperature, remaining fuel and wetness.

Extinguishing elements (e.g., the water-foam mixture ejected from the fire hose) were modeled so that the contact of the generated particles with a burning object causes a temperature loss. If the temperature goes below the ignition threshold, the fire is extinguished, and the part becomes wet. Further exposure to heat will eventually dry the part, bringing it back to the initial state, though with a lower amount of fuel.

To manage the effect of fire on the human body, it was necessary to introduce a gamification element. Each character is provided with a health value at the beginning of the simulation, and any exposure to harmful elements has the effect of lowering this value. A direct contact with flames or extreme heat, for instance, will cause a moderate damage, and will be signaled by playing a scream sound from the given character. When the health value reaches zero, the simulation is terminated for the user (who is considered as dead for purpose of the assessment).

Regarding the smoke, a box roughly approximating the tunnel shape was used as domain for the FDS

Figure 5: Road tunnel fire (first picture) and some of the available interactions: hazard lights, safety brochure, SOS button, extinguisher, vehicle engine, SOS telephone, SOS shelter doors, fire hose, NPC firefighter, scissors, and handline nozzle.

simulation. The fluid flow, provided in Eulerian representation, was a matrix of $4000\times17\times831\times17$ (time [s], width [m], length [m], height [m]) elements indicating an intensity value of smoke (in the range 0–255) in a given space coordinate for each time step. Data were sub-sampled with a $3\times3\times3$ linear filter to obtain a $4000\times6\times300\times12$ data structure, in order to lighten the computational load on the overall VR simulation. Then, the resulting grid was used to generate a set of billboard elements with their opacity proportional to the intensity value of each grid point, which are updated over time as the VR simulation progresses. The grid's higher vertical resolution was adopted to better represent the smoke layering phenomenon.

Smoke intoxication was managed separately, by periodically testing the presence of users inside the gas cloud, and triggering the intoxication effect if the test is positive. This condition, signaled by a coughing sound, causes a slow but continuous health reduction as the user remains inside the smoke-filled area.

4.5 User Assessment

The assessment module was designed to provide a summary of the user's actions with respect to the selected role. In case of civilians, the system displays whether or not the user:

- maintained the safe distance with the car;
- turned off the engine;
- enabled the hazard lights;
- pressed the SOS button;
- used the SOS telephone;
- tried to use the extinguisher on the fire;
- survived by reaching the shelter.

Along with the timestamp for each action. For the firefighter, the system shows whether:

- the presence of civilians was checked;
- the operator kept a safe distance from the fire;
- the fire was attacked correctly (from the base);
- the scissors were used correctly (far enough from the civilian's body to avoid causing injuries);

- the procedure was completed (the fire was extinguished).

5 CONCLUSIONS

In this paper, a road tunnel fire simulator in VR with multi-role and multi-user capacity is proposed. The system is designed to take advantage of a wide set of VR technologies and devices with the aim to maximize the fidelity of the experience when better hardware configurations are available, without introducing technological barriers. The multi-role and multi-user capabilities are complemented with a NPC logic to easily scale down to smaller user counts.

The devised assessment features make the simulator suitable for a number of different uses, from the training and evaluation of firefighting operators, to the study of the behaviours of individuals during the depicted emergency, as well as to communicate the security prescriptions to civilian users, being them professionals (e.g., truck drivers) or not. Furthermore, the use of gamification elements such as the concept of survival/victory opposed to wrong behaviour/loss are expected to lead to a positive attitude of the users towards the tool. A serious game, in fact, can be perceived as a challenge, that could push users into improving themselves by learning from their mistakes.

Future works will be initially devoted to the validation of the presented tool, by involving a relevant number of tunnel firefighting operators and by collecting their subjective feedback. Afterwards, the tool will be used to investigate the effectiveness of the training experience when compared with traditional training methods, as well as to study the contribution of each configuration (in terms of devices and technologies) with respect to the training purposes.

Moreover, the scenario will be also exploited to evaluate the effectiveness of the safety equipment reproduced in the VE, with the aim to constantly improve the overall tunnel safety. In fact, since civilians do not have any strict or mandatory objective in the simulation (except to survive), it would be possible to analyze the different trends regarding, e.g., the adherence to particular prescriptions, the use of specific equipment, and the order in which actions are performed. Still regarding non-professional roles, the effects of the VR-based training on long-term knowledge retention will be investigated by comparing it with the sole use of the safety brochure.

Furthermore, the multi-role feature could be exploited to study the benefits of role rotation in two different ways. Firstly, by putting users with a given role in the perspective of all the other roles, with the aim to increase the awareness of everyone's goals, improve individual behaviors and, consequently, the effectiveness of the shared experience; for instance, a civilian could be more prone to rapidly reach the SOS shelter when knowing that the firefighters cannot begin the extinguishing if there are still users scattered inside the tunnel. Secondly, a rotation within similar roles could be studied with the aim to increase preparation for any contingency; in this case, further playable roles would have to be developed (e.g., for the operators only one firefighter role out of the two depicted ones can presently be controlled by human players).

Among the future technical developments, there is certainly some room for improvement for both the fire and smoke representations. Regarding the former, a more physically accurate fire spreading model could be developed, still ensuring, however, real-time performance. For the latter, ways to introduce a certain degree of interactivity could be studied, e.g., by interpolating different simulation results to implement events of interest (like changes in the ventilation, etc.). Moreover, the multi-user, multi-role experience could be expanded into a completely customizable tool. In this way, a firefighting trainer could be able to define new use cases and scenarios on-the-fly, by adding and removing roles, vehicles and other elements, without requiring software modifications. In this context, NPC roles such as the fire truck driver could be made human-controllable, and methods to effectively simulate all the possible interactions between firefighters (e.g., the touch, useful in case of low visibility) could be investigated too.

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