A Virtual Firefighting Simulator

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1 Abstract

A simulator will be presented which employs VR techniques in order to provide a training environment for fire-fighters. While existing systems for fire-brigade training do focus on tactics and command training, this simulator targets the training of the fire attack group. It provides scenarios for search & rescue operations, direct firefighting using water and foam as well as radiation source search operations.
Visual, audio and haptic feed-back is provided. The system supports immersive displays (HMD) as well as standard techniques (monoscopic big-wall). It implements a walking paradigm, which enables the trainee to move around freely.
The simulator uses extended reality features in order to improve the handling (nozzles, dose meter, ...). The trainee can use the system fully equipped, even using the respiratory protection, in order to provide a realistic feeling.
Several physical models are used to provide effects closed to reality, namely:

- heat release rate is used to model the energetic behavior of a fire, flame size etc.
- a simple energetic model for fire-extinction by cooling
- water and foam ejection (depending on pressure, volume, form of jet, agent)
- a smoke system (visibility equivalent to height of eye)
- superposition of radiation sources (no shielding) and detection by Teleprobe FH40G

The simulation is supervised by an instructor, each action, e.g. radio traffic, movements is logged for analysis.

2 Introduction

Firefighter and other rescue personal needs to be trained regularly in order to react properly in complex situations. The very important aspect of collaborative operation between different personal can almost be trained in virtual environments [1], [2], [3], [4].
For the individual member of a rescue team, e.g. the attack crew a fully immersive training environment is needed to train special actions like fire extinguishing, movements and tactics [10]. These environments can be set up as scaled real world environments [5]. They are expensive and, although they are quite save, do adhere threads to the health of the user. These environments could be transformed into virtual reality environments if the appropriate system follows the main "principle of space and cyberspace" as described in [6]. These principles map real world experience to VR concepts.
Nether the less these real world training facilities can not be fully replaced by pure VR systems as they do provide experiences which can not be simulated right now (heat, free physical movement, mechanical limitations while handling hoses and nozzles, ...).

3 Methods

As proposed by Zeltzer [11] the concept of presence, interaction and autonomy lead to immersive VR environments.

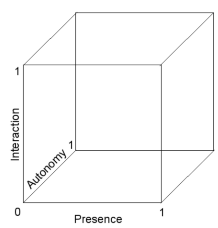

Figure 1: Zeltzer Cube

3.1 Presence

The experience of the virtual world should be closed to reality. Therefore a system should produce data for vision, hearing, touch, balance & kinesthesia, taste, smell.

3.2 Interaction

Firefighter interact using several devices like nozzles and radio. These devices should provoke appropriate changes in the simulation.

3.3 Autonomy

The state of the system should strictly follow physical rules independently. In most real world fire training setups an operator decides if a fire is extinguished manually!
Recent advances in the correct physical simulation of fire, fire spreading and evolution of fire provide the basis for the computer simulation of hazardous scenario [8].
The application of these concepts for a firefighting simulator is discussed in the following chapters.

4 The Firefighting Simulator

4.1 System overview

The system presented here provides a specialized user interface and standard output technologies. The simulation is driven by a simulation-engine which can provide hazardous scenario (fire, explosion, injured person, radioactive sources).

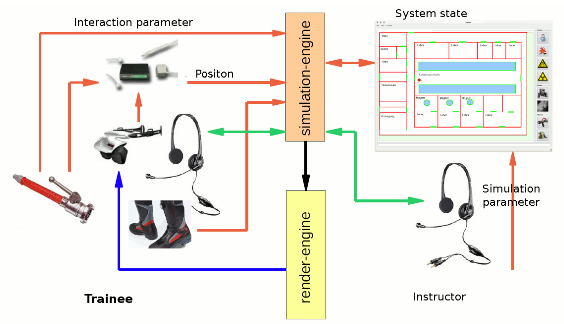

Figure 2: System overview

The trainee is equipped with a tracking system to estimated her/his position and orientation in the virtual world. A head mounted display is used to provide visual perception. The display is driven by a render engine which loads static geometries via VRML formatted files. The render-engine provides functions for visualizing fire, smoke, explosions and persons.

4.2 Render-engine and display system

The render engine is simple OpenGL application which runs standalone and receives visualization parameters via the network. It can produce monoscopic and stereoscopic (anaglyph, dual-head stereo, frame sequential stereo) output. Fire (flames) are modeled as multi-particle systems. Smoke is displayed employing the glFog capability combined with a horizontal, transparent top-plane.
Currently either a head mounted display (eMagin Z800) or a big screen rear-projection with active stereo (Xpand IR shutter glasses) is used. While the big screen projection could be used by a crew, the HMD provides full immersion into the training environment.
For fire engagement scenario a stereoscopic output is usually not necessary as in most cases the crew will experience dense smoke with rare visibility conditions. Combined with a set of speakers the trainee will perceive audio-visual output (explosions, crying people, ...). All other senses are not touched, as the appropriate output hardware is not available or too expensive. Taste and smell can be disregarded as crew is usually equipped with respiratory protection system.

4.3 User input

In order to compute correct visualization parameters the simulation must know about the position of the trainee. Therefore the trainee is attached to a head tracking system (polhemus Patriot). Although the tracker allows to find the relative position this is not sufficient to enable the trainee to perform a walk-through in a natural manner. As virtual floors are still subject to research (Cybercarpet) or too expensive (Virtusphere) this technology is not available here. It can be approximated by a "walk-in-place" paradigm. The trainee is attached to a step-sensor which allows movement in the viewing direction.
As different scenario require different devices a set of several virtual devices is available (e.g. a C-size nozzle and a Teleprobe FH40G dummy).

4.4 Simulation-engine and scenario

Prior to start, all parameters of an engagement are defined by an instructor. A scenario can be a combination of different basic scenarios. The instructor can change the scenario any time during the simulation. The operation of the simulation-engine will be discussed by example.

4.4.1 Search-and-Rescue operation

Objective: one or more missing person need to be located (and rescued).
First responders usually assigned the task of exploring the scene and perform basic rescue operation, mainly rescuing (disabled/insured) people from the hazardous environment. They therefore need to train communication skills and procedures of exploration.
The system described here emulates radio-communication via head-sets attached to a multi-channel sound-card. All radio-traffic is logged and can be analyzed later.

Tactics for search and rescue procedures vary on different environmental parameters like (building) geometry, including dynamic geometries, visibility (smoke), heat and others.
Free movement and proper visual presentation is required to train proper response. The system uses a polhemus Patriot tracking system [12], which provides stable location and orientation data. These data are transformed into a position in the virtual environment. As the detection range of the tracking system is limited and the user is bound to a certain area because of cabling, free walk is possible only in a very limited space. To break this limitation a virtual walking paradigm is implemented, using a stepping-sensor (simple switch) which is attached to the foot-wear of the trainee. Each "step in place" is interpreted as a step into the direction of the current view. While the height of eye and orientation of the trainee is provided by the tracker, "free" movement within the virtual world is possible.

Figure 3: position sensor mounted to helmet

In order to provide stress to the trainee (as she or he will experience in real environments) one or more casualties are placed in the scenery.

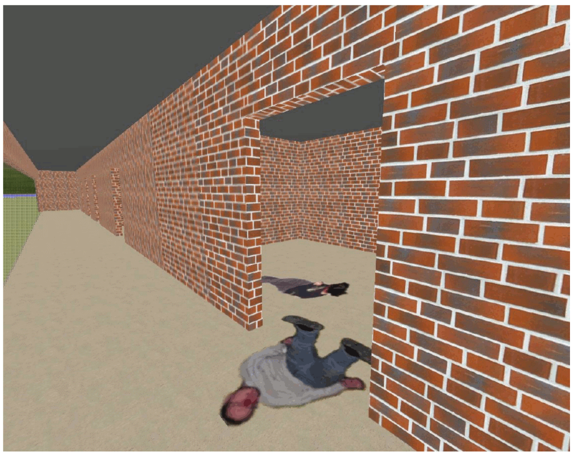

Figure 4: Search & Rescue Mission view

Depending on the state (in danger, escaping, immobile, rescued) of the casualty, its grade of injury (not insured, light, medium, heavy) and the vital state (NAD, unconscious, apnea, cardiac arrest) different presentations for visual and audio perception (cries, moaning) are generated. The perceived sound level represents a superposition of all currently placed casualties.

4.4.2 Radiation protection

Objective: estimate activity, locate one or more radiation sources.
Radioactive materials are widely used in medicine, industry and research. Therefore rescue workers have to prepare for scenarios involving radioactive materials. The main tasks consist of:

1. determining contaminated area
2. rescue people from "dirty area"
3. determine grade of contamination of persons
4. prevent other areas from contamination
5. locating radiation sources

To perform these operations firefighters are equipped with activity sensors (e.g. Teleprobe FH40G). Training the use of these devices usually requires real (but small) test sources. These source have to be supervised by specialized personal. Which makes training expensive. As physical laws of measurement are well known (and quite simple) they can be implemented very easy in a virtual environment. This system handles a set of radiation sources which are parameterized by the isotope and activity. In Germany rules of engagement are given by [13]. Three types of detection are required: dose rate for localizing "dirty" areas and estimation of threads, doses received and proof of contamination (proof of activity). While activity is directly correlated to the activity of the source, dose rate and dose are measured indirectly. To simulate the effect of dose rate, the so called "dose conversion factor" DCF can be used to compute the dose rate H from the activity A

$$H = DCF \cdot A \tag{1}$$

Doing a superposition on all sources in the virtual environment the dose rate at a certain point xp can be estimated by

$$H_P = \sum DCF_i \cdot A_i \cdot \frac{1}{\|\underline{x}_i - \underline{x}_p\|^2} \tag{2}$$

where x_i is the position of source. As the geometry and materials, the virtual world consists of, is known, damping could be taken into account (not implemented currently). Because the Teleprobe FH40G does not have directional characteristics, the estimated value represents the one which would have been measured in a real environment.
The computed value (H_P) is mapped to the virtual display of the Teleprobe FH40G. The user controls the location and orientation of the Teleprobe in the virtual world using a dummy with a second scan-head attached.

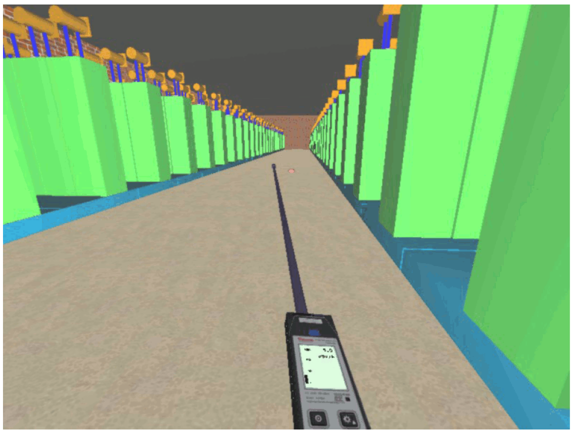

Figure 5: Doing exploration in a "dirty" environment

4.4.3 Firefighting

Objective: locate fire, fight fire
Fighting a fire itself is considered one of the main tasks of fire brigades. To perform this task well a lot of experience is required. These skills have to be trained regularly. Nowadays real world training is performed using wood or gas heated fire houses (fig. 6). These installations allow training under realistic but controllable conditions.

Figure 6: Fire-house training (FF Rudersdorf, Austria)

As knowledge about the physical and chemical processes of fire extends it is almost possible to simulate standard situations, including flash-over and back-draft.
Modeling the behavior of fire is a complex task. Currently most models employ continuous fluid dynamics methods on compressible media to calculate the combustion process [8], [14], [15]. These methods are very advanced but require a lot of computational power. For a training environment it might be sufficient to reduce the complexity of the model and do a rough estimation of the combustion process employing the concept of heat release rate [9], [?]. For simple materials the heat release rate $\frac{dq}{dt}$ (HRR) can be deduced from

$$\dot{q} = \dot{m} \cdot \Delta H_c \tag{3}$$

Where $\frac{dm}{dt}$ is the mass loss rate and ΔH_c is the known lower heat of the material. HRR itself gives an estimate on the heat per area released at a certain time t. If the material is a composite the HRR could be measured by a calorimeter [17].

Figure 7: Combustion of Bunk Bed

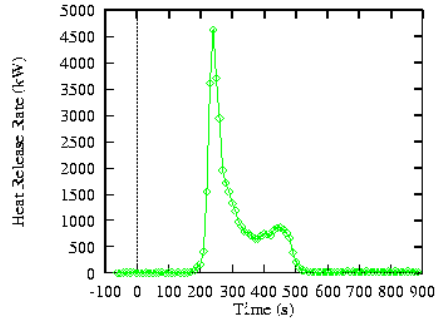

Figure 8: HRR measured for burning of bunked bed

Given a certain material, its mass, the HRR and the size of the burning surface, the heat emitted by the fire can be estimated by

$$Q_F(t) = \int \dot{q} \cdot A_F dt \tag{4}$$

[18] suggests a very simple correlation between average flame hight and mass loss rate.

$$log(h_F) = -0.38 + \frac{1}{2} log(\dot{m}) \tag{5}$$

As the mass loss rate can be computed from (3), all necessary parameters for creating an appropriate visual representation of a fire are available now. Flames are commonly displayed using multi-particle systems with textures. With respect of the chaotic nature of flames, the following generator is used

$$\underline{x}_i = \begin{pmatrix} r_F \cdot rnd \cdot cos(2\pi \cdot rnd) \\ r_F \cdot rnd \cdot sin(2\pi \cdot rnd) \\ v \cdot rnd \end{pmatrix} \tag{6}$$

with breaking condition $x_z < h_F * rnd$. An example snapshot of the resulting fire representation is shown im figure 9.
With that model even flame drift can be visualized to improve perception.

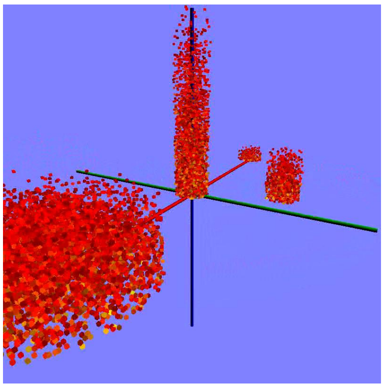

Figure 9: flame generator example

Concept of fire extinction

From the combustion triangle the main concepts of fire extinction can easily be deduced:

- extinction by cooling
- extinction by smothering or replacing oxidant
- extinction by removing combustible

The process of extinction by cooling can be modeled using the following relation:

$$Q(t) = Q_F(t) - \int \dot{q}_L dt - Q_{CTR} \quad (7)$$

Assuming the fire to be defined by its area A_F and its HRR and assuming a "flat" behavior of the extinguishing agent. $\dot{q}_L$ is approximated by

$$\dot{q}_L = \frac{A_{LF}(t)}{A_L(t)} \cdot I_L(t) \cdot C_L \cdot S_L(t) \quad (8)$$

Where $\frac{A_{LF}}{A_L}$ defines the ratio of the agent applied to the fire (A_L is considered to be the area on the ground covered when the agent's jet hits the ground, A_{LF} is that part of A_L which overlaps with A_F). $I_L(t)$ gives the volume per time, C_L the heat capacity and $S_L(t)$ a measure of effectiveness of the agent (e.g. depending on the drop size). Usually $I_L(t)$ and $S_L(t)$ will have discrete values given by the extinguishing device used.
The fire will extinguish if the combustible is gone (mass loss rate) or if the temperature at the surface of the combustible falls below the ignition point of the combustible. At this point conduction, transmission and radiation of heat should be taken into account, which again leads to very complex models. Here these effects are modeled by a constant correction-term Q_{CTR}. The temperature in question could be determined by

$$dQ = C \cdot m \cdot dT \quad (9)$$

Where C and m are specific constants given by the combustible-air interface. In order to find A_L and A_{LF}, the trajectory of the extinguishing agent needs to be modeled. For "heavy" agents like water, low- and medium expansion foam this can be done by modeling the jet consisting of a set of particles. The trajectory can be computed as

$$x_n(t) = \frac{m_p}{\beta} \cdot v_0 \cdot cos\alpha \cdot \left(1 - e^{-\frac{\beta}{m_p} \cdot t}\right) \quad (10)$$

and

$$\begin{aligned} y_n(t) &= \frac{m_p}{\beta} \cdot v_0 \cdot sin\alpha \cdot \left(1 - e^{-\frac{\beta}{m_p} \cdot t}\right) \\ &+ \left(\frac{m_p}{\beta}\right)^2 \cdot g \cdot \left(1 - e^{-\frac{\beta}{m_p} \cdot t}\right) \\ &- \frac{m_p}{\beta} \cdot g \cdot t + h_0 \end{aligned} \quad (11)$$

Fig. 10 shows simulated trajectories with respect to the attack angle α.

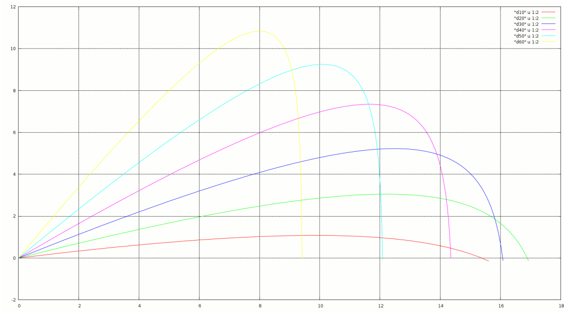

Figure 10: Trajectory examples

The air resistance β depends on the form (full beam or spray) and the expansion rate (if foam is simulated). The mass m_p is determined by the delivery pressure, the density of the agent and the cross-section of the hose

$$m_p = A_0 \cdot \sqrt{2 \cdot p \cdot \rho} \cdot dt \quad (12)$$

Assuming no pressure loss in the fire hose, the discharge velocity v_0 can computed by

$$v_0 = \sqrt{\frac{2 \cdot p}{\rho}} \cdot \frac{A_0}{A_1} \quad (13)$$

Where A_1 is the cross-section at the nozzle.
Finally, the trajectory is mapped to a plane orthogonal to the ground, where the direction of this plane is defined by the azimuth angle γ of the nozzle.
The parameters are controlled using a modified C-size nozzle with a second polhemus scan-head attached at the end of the nozzle. The trajectory plane is translated to the absolute position of the nozzle defined by

$$\underline{\tilde{x}}_n = \underline{x}_{AT} + x_n(t) \cdot \begin{pmatrix} cos\gamma \\ sin\gamma \\ 0 \end{pmatrix} + y_n(t) \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (14)$$

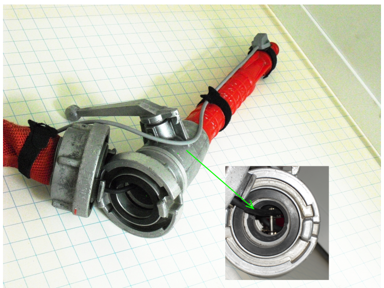

Figure 11: modified C-size nozzle

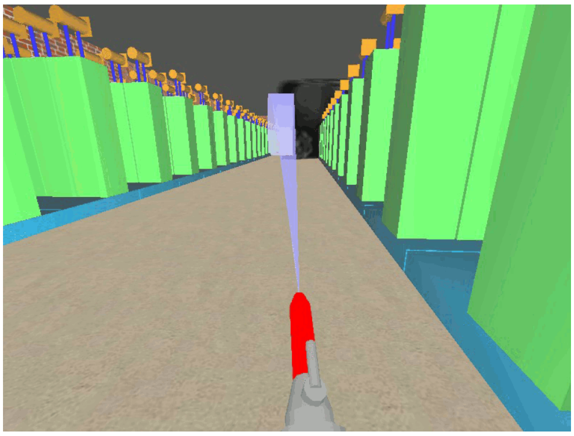

Figure 12: Firefighting using C-size standard nozzle

The simulation engine permanently monitors the extinction parameters and computes the process parameters in real-time. The visualization is updated in real-time too.

5 Conclusion

The system is operational and was presented on several occasions. Some tests showed, that free movement is limited if using the big wall setup. Therefore the fully immersive setup using a head mounted display should be used for "free" training, while the big wall setup could be used to train actions which do not require a walk-trough.

The implementation of the basic scenarios have been confirmed to be appropriate in presentation and behavior. The correct (physical) behavior of the processes simulated still needs to be veryfied. A first experiment showed reasonable results [19].

Future extensions will include autonomous persons and better fire simulation using the FDS.

Using the system in addition to real world training facilities - either to prepare a real world training or to train particular situations - could help to improve the abilities of firefighters.

Figure 13: Principle usage of the simulator in a big wall setup

6 Acknowledgements

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Fig. 6: Freiwillige Feuerwehr Rudersdorf (Austria)
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