The Research of VR-based Evacuation Commander Training System for Tunnel Fire

Min Hu and Biwen Liu

ABSTRACT

In order to control the economic and social impacts of tunnel fire, a training system based on virtual reality technology is developed to train fire evacuation commander. This system collects action and voice commands through virtual reality device, and dynamically updates the evacuees’ behaviors. Combining with the fire scene and real time status of evacuees, this system simulates the evacuation process and assesses the numerical effect of commander intervention. The simulation experiment of Dalian Road tunnel model is taken as an example to demonstrate the effectiveness of the training system.1

INTRODUCTION

With the rapid development and expansion of Chinese highway tunnel system, tunnel accident has drawn increasing attention, especially for fire accidents. Previous studies show that building fire is one of the most frequent occurred disaster that causing huge economical losses and large number of casualties [1]. Meanwhile, smoke and high temperature that released by fire not only damage tunnel structure but also hinder the evacuation process. Fire drill for enhancing fire knowledge and improving evacuation efficiency could reduce the loss significantly. However, it consumes large amount of manpower and resource while this kind of exercise is difficult to simulate the actual fire scene during the training process. Therefore, the

1Min Hu, Biwen Liu, Sydney Institute of Language and Commerce, Shanghai University, Shanghai 201800, China.
Min Hu, Biwen Liu, Joint Research Center for Construction Industrialization of SHU and SUCG, Shanghai 200072, China.
use of computer technology and virtual reality (VR) for simulating evacuation becomes an important method in the realm of fire evacuation research.

In the field of evacuation research, simulation software like EVACNET, FDS+Evac, Simulex and building EXODUS are widely applied. These software show difference in fidelity and real-time performance, however, lack interactivity in general. As a result, above applications are used usually in evacuation process research rather than fire evacuation training. Therefore, researchers proposed various interactive simulation methods. Rüppel and Schatz [2], Ren et al., [3] and D’Orazio et al., [4] applied wearable game devices to enable object handling operation in simulated scene. Zhang Jingzong [5] proposed an interactive fire simulation method that focuses on the use of fire equipment. Zhu Hongqing [6] et al. did not only realize the interaction of equipment operation, but also evaluated the performance of user’s operation. These studies mainly concentrated on the interaction between evacuee and the fire scene, except Zhu Hongqing, [6] whose simulation is designed for firefighter rather than ordinary evacuees. Lu Jun et al., [7] considered the decision-making process of commander. However, in terms of implementation method, they observed the occurrence and development of fire accident with the purpose of assisting decision-making rather than observing the dynamic impact of commands on evacuees. In general, most previous studies focused on the training of evacuees but seldom explored the interaction between commander and evacuees. For tunnel fire, however, the proportion of floating population is higher compared with ordinary buildings, which leads to the low feasibility and efficiency for conducting fire drills. Therefore, it is more feasible to train commanders in order to improving evacuation efficiency and reducing the number of casualties.

This paper develops a tunnel evacuation commander training system based on VR. This system uses Kinect as input device and presents the whole evacuation process based on UC-win/Road simulation software. In the simulated tunnel environment, the influence of commands on evacuees can be simulated by collecting commands through VR input device. This system provides evacuation commander with an integrated training system that can reduce the loss.

THE FRAMEWORK OF VR-BASED EVACUATION COMMANDER TRAINING SYSTEM

The purpose of proposed system is to simulate the actual interaction between commander and evacuees under the fire scene so as to achieve a better training efficiency. In actual fire, the commander generally uses both action and voice commands to influence evacuees. In order to capture these commands, this study uses the Kinect as an input device to collect user commands. In addition, the dynamic fire scene and the current status of evacuees also affect the commander’s decisions. The user of this training system needs to obtain the above information to make decision. Based on the requirements and the existing technology, this paper designs a VR-based Evacuation Commander Training System (ECTS).
The mechanism ECTS is shown in Figure 1. There are three main functional modules, the evacuee simulation module, command processing module and interactive feedback module. The main mechanism is as follows: Firstly, evacuees is generated by evacuee simulation module and presented together with fire scene to the user via the interactive feedback module. Next, the user receives information and decides the command to be issued according to the real-time information displayed in user interface. After the Kinect collects commander’s action and voice commands, command information is transferred to command processing module to update the status of evacuees. This process is presented to the user through interactive feedback module in real time. In the whole simulation process, the three modules are updated continuously until the interactive feedback module detects the end simulation signal. Final evacuation results will be presented to the user after simulation is completed.

**EVACUEE SIMULATION MODULE**

Evacuee simulation module is responsible for generating evacuees in simulated environment without command influence and then controlling the change of evacuees’ behavior pattern and status. It receives the user’s settings for simulation parameters and translates them into effects on evacuee behavior patterns and then keeps updating the status of evacuees in real time.

Simulation parameters are the main inputs for evacuee simulation module. Due to the difference of tunnel structure and ventilation facility, vehicle density in the same tunnel could change dramatically in different time periods. Therefore, for each case, input parameters need to be set to simulate a particular situation. Simulation parameters can be divided into two categories as shown in TABLE I. The evacuee
parameters describing the composition of evacuees and the fire parameters describing the fire scene.

### TABLE I. LIST OF SIMULATION PARAMETERS.

| Parameter type   | Parameter name            | Description                                      | Unit / Measurement |
|------------------|---------------------------|--------------------------------------------------|--------------------|
| Evacuee parameter | Total number (N)          | Total number of evacuee                          |                    |
|                  | Sex ratio (RS)            | The percentage of women                          | %                  |
|                  | Rate of disadvantaged (RD)| The percentage of disadvantaged                  | %                  |
| Fire parameter   | Temperature (T)           | The average temperature in the fire              | ℃                  |
|                  | Harmful gas concentration (ρ)| Concentration of harmful gas                | %                  |
|                  | Level of evacuation sign (l₅)| Evacuation signs within the building are sufficient and clear | Low/ Mid/ High |

Based on evacuee parameters, evacuee simulation module generates a random initial position for each evacuee and updates status continuously. The evacuation route is based on the particular contingency plan formulated in advance, and is preset in the form of flight path in the simulation software. In this system, there are four types of status of evacuees, which are waiting, evacuating, evacuated, and dead.

1. **Waiting**: The initial state of all evacuees at the beginning of the simulation, after a certain reaction time \( t_{r} \), the status of evacuee changes to evacuating.
2. **Evacuating**: Evacuee moves to safety exit at speed \( V \) along the preset evacuation route.
3. **Evacuated**: Once the evacuees arrive at the end of their evacuation route, the evacuation status changes to evacuated status.
4. **Dead**: When survival time \( t_{o} \) runs out, the status changes from evacuating to dead.

**Reaction Time**

Reaction time is the time period that a person spends from the beginning of fire to start evacuating. According to Lo's research on fire survivors, the distribution of people's actions and the time they take after accident happens are shown in Figure 2[8-9]. The ECTS is based on this survey, using the behavioral distribution and the decision-making time shown in Figure 2 to calculate the reaction time.
Evacuation Speed

The evacuation speed is defined as evacuee’s normal speed without impact from evacuation commands. Due to the narrow tunnel space and the simple arrangement of obstacles, the evacuation can basically be regarded as a lined-up flow of evacuees, so the overall evacuation speed is greatly influenced by the crowd composition. In addition, the setting of the evacuation signs will also affect the overall evacuation speed. Therefore, the system adjusts the preset evacuation speed through three parameters, including age ratio, ratio of disadvantaged and evacuation sign setting. The expression of evacuation speed $V$ is as formula (1-2).

$$V = V_0 + (RD_0 - RD) \cdot V_w + (RS_0 - RS) \cdot V_F + V_s \quad (1)$$

where

$$V_s = \begin{cases} 
-0.5, & L_s = Low \\
0, & L_s = Medium \\
0.5, & L_s = High 
\end{cases} \quad (2)$$

$V_0$ denotes the default evacuation speed, $RD_0$ is the default ratio of disadvantaged, $V_w$ refers to the impact level of age rate towards the overall speed, $RS_0$ is the default sex ratio, $V_F$ is the impact level of sex ratio towards the overall speed.

Survival Time

Survival time is a measurement of how long a person lives in the fire scene. Xie Xuyang et al., [10] calculated the survival time of evacuees and pointed out two major factors of fire death: high temperature and harmful gas. To calculate the endurance time of evacuee in these two environments to predict the overall survival time, this paper defines that the endurance time under high temperature is $t_1$, the
endurance time under harmful gas is $t_2$. The smaller value of $t_1$ and $t_2$ is used as the survival time of an evacuee, as shown in formula. (3-4).

$$t_s = \min (t_1, t_2)$$  \hspace{1cm} (3)

where

$$t_1 = \frac{4.1 \cdot A \cdot 10^9}{T^{3.61}}, \quad t_2 = 160.06 \cdot \exp(-3.96 \cdot \rho) - 11.14$$  \hspace{1cm} (4)

$A$ is a random value that indicates the difference of people's tolerance to high temperature.

**COMMANDPROCESSING MODULE**

The command processing module exerts influence from commander on evacuees to make them under control. It collects voices and actions from commander through Kinect and then translates them into commands that can be understood by the computer. Kinect is a motion sensor of Microsoft. It recognizes voice commands by confidence interval analysis of collected voices and key words, and action commands by tracing the movement of human joints. The ECTS defines four action and four voice commands, as shown in TABLE II. Seven of them act on evacuees, while action “Move” simulates the movement of commander. It controls the position of user and shifts the coverage of commands, meanwhile updates the view in user interface.

The command processing module transforms actions and voices of users into strings, and then commit to the UC-win/Road plugin that controls dynamic simulation. After receiving commands, the plugin updates their effects on evacuees and the user interface. An example of the command response process is shown in Figure 3. Evacuees in ECTS are generated as instances of the “Person” class, whose public methods are aimed to read and edit evacuees’ properties and then update changes to 3D character models in simulation. Once receiving a “Fire” command, the command processing module reads status and positions of every evacuees to judge whether they are on waiting state and in the coverage of commander. Then the wait time of eligible evacuees would be reduced and reflected on character models. Above judgement and reflection are implemented in each Kinect frame.
TABLE II. DEFINITION OF COMMANDS.

| Name        | Move                      | Raise                      | Whistle                  | Lateral Raise          |
|-------------|---------------------------|----------------------------|--------------------------|------------------------|
| Action      | Raise right hand above head and drag with fist clenched | Raise left hand above head | Put left hand in front of the mouth | Raise both hands |
| Response    | Change the position of commander | Speed up evacuees         | Reduce wait time of evacuees | Speed up evacuees slightly |

Voice Commands

| Name        | Command               | Speed up                      | Lead                      | Crawl                   |
|-------------|-----------------------|-------------------------------|---------------------------|-------------------------|
| Command     | Fire/Fire Alarm       | Hurry up/Speed up             | Come this way/Go this way | Crawl/Crawl Forward     |
| Response    | Reduce wait time of evacuees | Speed up evacuees          | Speed up evacuees slightly | Speed down evacuees and lengthen survival time |

Figure 3. The response process of “Fire” command.

INTERACTIVE FEEDBACK MODULE

The response feedback module manages outputs of ECTS. It presents visual field and decision-making assist information to commanders in the simulation, and deal with simulation results after the simulation. The interactive feedback module provides two views for users, which are first-person view and evacuee distribution view, as Figure 4 shows. The first-person view displays and changes current visual scene along with the movement of commander. Therefore, commander can observe states of surrounding evacuees to give practical commands. Besides, these commands are shown in the interface so that commander is able to realize maloperation and take actions promptly. On the other hand, the evacuee distribution view is a top view of the whole tunnel. The interactive feedback module collects positions and living states of all evacuees, and reflects with red-green dots above the
tunnel in real time. Effective range of command is also labelled in this view, which enables commander to make moving decisions according to evacuees’ distribution.

Once none of evacuees’ state is waiting or evacuating, the simulation is finished. The interactive feedback module summarizes assessment indicators and calculates these indicators in the condition of no commander intervention, so that compares them to assess intervention effect. Assessment indicators include evacuation time and death toll. The evacuation time is concluded by compare the finish time to start time of simulation, while death toll is counted by inspect states of all evacuees. In the condition of no commander intervention, the evacuation time \( t \) and death toll \( d \) is calculated as formula (5-6).

\[
t = \max_{1 \leq n \leq N} [t^n_w + \min(t^n_s, t^n_e)], \quad d = \sum_{n=1}^{N} D_n
\]

where

\[
t^n_e = \frac{s^n}{v}, \quad D_n = \begin{cases} 0, & t^n_e \leq t^n_s \\ 1, & t^n_e > t^n_s \end{cases}
\]

\( s^n \) is the evacuation distance of the nth evacuee. \( t^n_w \) is the wait time, \( t^n_e \) is the survival time and \( t^n_s \) means the theoretical evacuation time of the nth evacuee.

EXPERIMENT

The fire environment used in this training system is Dalian Road tunnel in Shanghai, which opened in 2003 with a total length of 2527 meters. As an important traffic tunnel connecting the prosperous areas with heavy traffic, Dalian Road tunnel will have serious consequences once the fire happens. Therefore, it is very important to ensure its evacuation efficiency.

The trained commander simulates in ECTS for 10 times under same parameters, results are shown in TABLEIII. Along with the increase of training times, death toll and number of saved people improves, which means the training can decrease death toll. However, evacuation time fluctuates irregularly and number of negative saved time increases. It is because that some of commands are able to lengthen survival time of evacuees, therefore total evacuation time increases when there are dead evacuees at the end of simulation. Overall, increasing number of saved people and more negative saved time indicate that ECTS is able to reduce casualties of tunnel fire by commander training.

Besides, there is abnormalities in this experiment. Firstly, the death toll is exorbitant. This may be led by two factors. The first one is the high concentration of harmful gas. Tunnels are longer and thinner, which blocks the circulation of air. So, ventilation is extremely important in reduce the impact of tunnel fire. The second factor is that origin of fire is set at the entrance of tunnel in this experiment, which means there is only one exit in this fire accident. Secondly, although there is no
action maloperation in experiment, voice commands have a 10\% chance of maloperation. The pronunciation of trained commander and recognition accuracy of Kinect are blamed for this defect.

![Figure 4. The user interface of ECTS.](image)

| Times     | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-----------|----|----|----|----|----|----|----|----|----|----|
| Death toll| 43 | 46 | 43 | 42 | 40 | 34 | 37 | 33 | 36 | 33 |
| Evacuation time | 9:32 | 10:22 | 11:47 | 11:51 | 10:26 | 9:38 | 12:01 | 10:49 | 11:17 | 11:03 |
| Saved people | 7  | 6  | 9  | 9  | 11 | 12 | 14 | 13 | 15 | 14 |
| Saved time | 84 | 29 | 72 | -37 | -23 | 53 | -2 | -52 | -31 | -58 |

**CONCLUSIONS**

This paper develops the VR-based ECTS for tunnel fire, and performs experiment on the model of Dalian Road tunnel in Shanghai. The ECTS achieves presentation of evacuee response to commands and numerical assessment of intervention effect by collecting action and voice commands from commander using VR device and simulating behaviors of evacuees through simulation software. Results of experiment indicate that trainings enable commander to take more effective actions to lengthen survival time of evacuees and reduce death toll of fire accident. Now the ECTS is developed on the premise that all evacuees respond in same mode. To improve the system, more various response mode of evacuees can be taken into consideration. Besides, a more accurate recognition of voice commands is also a reasonable improvement direction.
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