Real-Time Evacuation Simulation in Mine Interior Model of Smoke and Action

Pengfei Huang, Jinsheng Kang, Joseph T. Kider Jr., Ben Sunshine-Hill, Jonathan B. McCaffrey, Desirée Velázquez Rios and Norman I. Badler
University of Pennsylvania - SIG Computer Graphics Center
{pengfei, kiderj, bsunshin, jmccaf, badler}@seas.upenn.edu, deveri@mate.uprh.edu
Brunel University - School of Engineering and Design
jinsheng.kang@brunel.ac.uk

Figure 1: From left to right: (A) Coal mine equipment models; (B) Simulation of a normal working shift; (C) Simulation results on evacuation as smoke begins to envelop the miners

Abstract

Virtual human crowd models have been used in the simulation of building and urban evacuation, but have not yet applied to underground coal mine operations and escape situations with emphasis on smoke, fires and physiological behaviors. We explore this through a real-time simulation model, MIMOSA (Mine Interior Model Of Smoke and Action), which integrates an underground coal mine virtual environment, a fire and smoke propagation model, and a human physiology and behavior model. Each individual agent has a set of physiological parameters as variables of time and environment, simulating a miner's physiological condition during normal operations as well as during emergencies due to fire and smoke. To obtain appropriate agent navigation in the mine environment, we have extended the HiDAC framework (High-Density Autonomous Crowds) navigation from a grid-based cell-portal graph to a geometry-based portal path and integrated a novel cell-portal and shortest path visibility algorithm.

Keywords: Simulation and Modeling, Virtual Crowd, Physiological Agent, Cell-Portal Graph.

1. Introduction

Coal fires are a frequent occurrence and a major threat to life and property in the mining industry. Coal burns very easily if oxygen is supplied, so any flame or spark could cause fire. These hazards arise from mechanical movements of mining tools where steel bits strike rock or pyrites, from slabs of roof falling against metallic surfaces in the working face (mining area), or from open lights or sparks in violation of safety standards [1].

Coal mine evacuation is very different from other evacuation scenarios such as from buildings. Miners evacuate along miles of long narrow tunnels in smoke and darkness, and the way out is limited to few openings. Toxic and explosive gases build up very quickly, and oxygen supplies may be insufficient. The miners' physiological and psychological states also affect their evacuation process.

Simulation research on mine fire evacuation is needed to develop new fire prevention and response measures. Our MIMOSA (Mine

Interior Model Of Smoke and Action) system provides a more realistic simulation platform that reproduces possible scenarios so miners and ground control officers may be better trained. This could help minimize life and property losses if a mine fire incident should occur. Virtual crowd models can be used to simulate building and vehicle evacuation; however MIMOSA provides a framework to additionally simulate physiological and psychological states of miners in underground evacuation. Current coal mine fire and smoke research doesn't integrate this 'human' model into the simulation. This paper describes integrating a real-time underground coal mine virtual environment simulation occupied by virtual miners with a simple fire and smoke propagation model. The human physiology and behaviors in mine fire evacuation process are based on a NIOSH summary [2].

MIMOSA extends a virtual human agent representation with a set of physiological parameters which are variables of time and environment. These variables track a miner's physiological condition during fire evacuation. For agent navigation in the complex mine environment we have extended our HiDAC crowd model from a grid-based cell-portal graph to a generic geometry-based portal graph with computed path visibility. We simulate coal mine fire and smoke propagation in real-time by employing classic mine ventilation network theory and without computationally expensive CFD calculations. This is the first attempt to simulate underground coal mine fire scenarios accurately and efficiently.

The rest of the paper is organized as follows. First we briefly review related work on coal mine fire and smoke simulation, and virtual crowd simulation in fire evacuation. Then we introduce our models for fire and smoke propagation, human physiology and human behavior. The MIMOSA integrated framework is described. We conclude with experimental results.

2. Related Work

Because of its potential safety impact, coal mine fire simulation is an active research topic. Many of the simulations are based on Computational Fluid Dynamics coupled with experimental research. For example, Vaught *et al.* use a 2D model to simulate the flow and temperature fields in underground coal fires [2]. Several mine fire simulation software tools have also been developed. MFIRE was first developed by Michigan Technological University under the sponsorship of US Bureau of Mines; while it was originally designed to simulate mine ventilation systems, it was later extended to simulate fire as well [4]. MFIRE does not integrate any miners into its model and it is computationally expensive to calculate. EXODUS, a sophisticated fire evacuation simulation tool, features fire and smoke propagation models, as well as human models, but lacks sufficient modeling capability to simulate human psychology, physiology, communication and decision-making processes.

3. Smoke Fire Model and Human Physiology Model

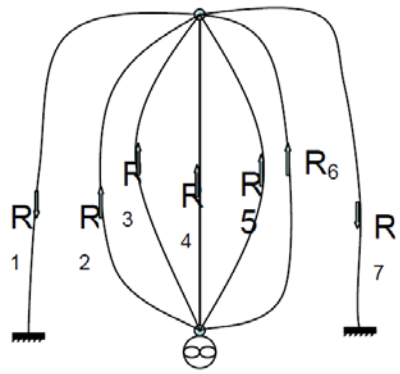

Figure 2: Simulated mine tunnel network

MIMOSA simulates fire and smoke based on classic mine ventilation network theory [6], which resembles electric circuits as shown in Figure 2. First, the airflow in all tunnels is calculated before the fire incident occurs, and then fire and smoke propagation are added to the network. The fire and smoke simulation is based on the Law of Mass Conservation and the Law of Energy Conservation.

In MIMOSA each virtual human agent has physiological parameters including O_2 intake rate, CO_2 expel rate, body comfort, and the agent's visibility. In order to connect the agents' physiological parameters with the smoke and fire simulation, we compute their experienced smoke and toxic level per Eq. (1):

$$TOX = \frac{ppmCO}{1500} + \frac{ppmHCl}{100} \le 1 \quad (1)$$

where CO is carbon monoxide, HCl is hydrogen chloride, and ppm is parts per million (gas units).

When *TOX* level reaches 0.1, people have difficulty breathing and experience eye irritation; when *TOX* level reaches 0.3, the environment will feel unbearable. These values are used in the virtual miners to trigger their reaction to the current *TOX* level. Each miner agent has a health variable; it is initialized based on body and changes accordingly to agent's current activity and location in the ambient gases of the environment [6]. Agent health parameter Basic Metabolic Rate (BMR) of human body is defined as Eq. (2).

$$BMR = 0.685W + 29.8 \text{ (Watt)} \quad (2)$$

where W in Kg is the body weight. Oxygen intake (Liter/Minute) can be defined as Eq. (3).

$$VO_2^{req} = \frac{Power \times 60}{20.92} \quad (3)$$

where Power is the body energy consumption per second (BMR) in KW.

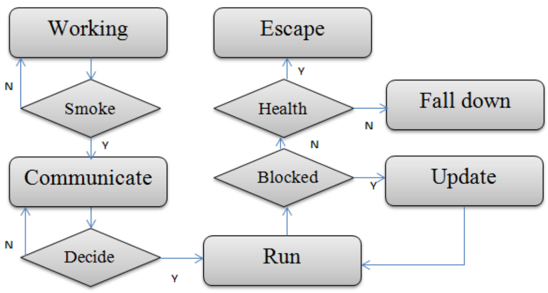

Figure 3: Agent state diagram

Figure 3 shows the main steps of the miner activity finite state machine. If there is no smoke, the miner will be working normally. If a miner detects smoke, the evacuation algorithm is triggered. First, the agents communicate to group together, and then they retrieve route information stored in the environment and decide on the shortest path for an escape route. In this phase the agents must escape from the vicinity of the smoke. Sometimes, the path will be blocked, and they must update the path information. If an agent's *TOX* value is too high, they cannot continue running and will fall down. Each state is associated with specific algorithms in the application framework. For example, the working state follows a schedule, and the communication uses a geometry computation to determine when the nearby agents can share information. The running state uses shortest path algorithms accessing a cell-portal graph. Pre-stored motion capture clips portray the miners' current activities.

MIMOSA leverages MACES and HiDAC [3]. MACES computes agent navigation corresponding to the path finding process of finding a viable sequence of rooms towards an exit, and HiDAC computes the agent's collision-avoidance motion within each room using social forces. Each agent has its own map knowledge which abstracts the environment geometry as a cell-portal graph, where the cells (nodes) are the rooms and the arcs are the portals between rooms.

The HiDAC framework originally used only rectangular grid-based geometry building structures, with doors between grid cells serving as both agent attractors and portals. However, typical mine layouts require more general shape and thus we modified the layout to function with triangle-shaped cells.

4. Extending HiDAC by Geometric Visible Path Search

Our agent navigation paths are computed over a triangle-based cell-portal graph. All the walkable areas on the floor are decomposed into triangular meshes. An agent will walk towards the farthest triangle based on its centroid visibility. We pick centroid here as to simplify the visibility problem. The visibility distance D determines which triangle the agent can see (Figure 4A). If the agent is in the starting cell 1and only cells 2, 3, and 4 are visible from 1, the agent chooses the path to the furthest visible cell 4 from 1. The path would be updated if the agent finds a closed portal door or an increased *TOX* level.

The algorithm's main cost is the query of agents versus cells and portals. Given *m* agents and *n* cells and portals, the complexity would be $O(m*n)$ initially, but it is largely reduced to $O(m)$ during run time by employing spatial hashing algorithms. Thus, the algorithm and framework successfully run in real-time.

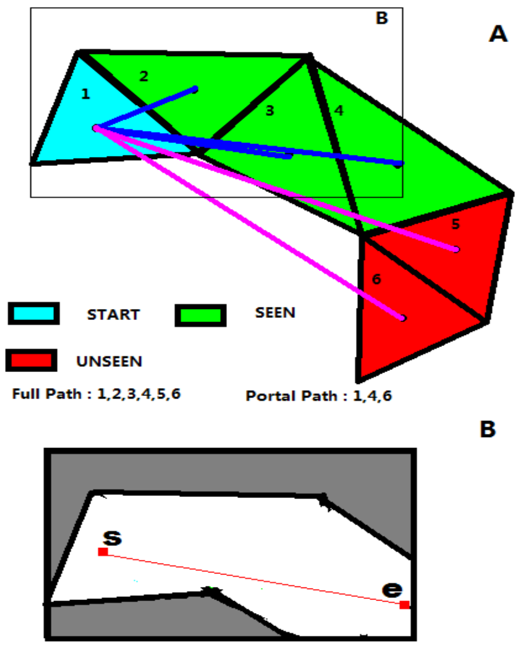

Figure 4: Cell-Portal path finding extending HiDAC; (A) path finding algorithm based on agent's visibility; and (B) is what the original framework solves.

5. Experiments

A realistic continuous mining operation was constructed in Maya (Figure 1A), including a mining machine, a roof bolter machine, two shuttle cars, a conveyor with dump point, a power generator or transformer, and a man-trip (people carrier). A view of the mine simulation is shown in Figure 1B and C. The scenario includes:

1) Normally the miners will be working around the mining machines as scheduled work.
2) If a fire starts, the agents gather together to have a short meeting to plan an evacuation path
3) Agents all try to escape based on the path.
4) Some agents successfully escape but some fall down because they are short of oxygen or experience high *TOX* levels.

As illustrated, a group of virtual miners have been successfully integrated with the underground coal mine virtual environment, fire and smoke propagation model, and the human physiology and behavior models using the integrated framework of HiDAC, MACES, and MIMOSA. Output graphics uses the OGRE 3D game animation engine [7], and the GUI framework is based on QtOgre [8].

For the future we need to include more characteristic and meaningful actions for the agents during their work shift. We should also extend the scenarios to more complicated settings including ramps, stairs and elevators. For safe design and safety training, the MIMOSA system should include analytical tools for assessing evacuation times and personal survival under easily modifiable mine configurations.

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