Fire Spreading Simulation in Large Buildings Based on Cellular Automata

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Abstract: - The buildings fire safety is currently an important subject for researchers and practitioners due to probable incidents that can happen inside industrial plants, large public buildings or transport facilities: fires, explosions, toxic releases, etc. Even minor events can seriously endanger life, goods and environment. Particularly, fire spreading in large buildings represents a major threat that can be investigated using computer simulation to reduce its severe consequences. The cellular automata based method presented in this paper represents a fast and interactive tool designed for fire spreading investigation in large buildings.

Key-Words: - fire simulation, cellular automata, transition rule.

1 Introduction

The fire safety issues become more and more an important subject in contemporary society. Generally speaking, larger and increasingly complex buildings together with the use of new materials can lead to more dangerous fires, where the increased hazards are difficult to predict. New risks arise due to the use of new chemicals, and also by transportation and handling of hazardous materials. The growing threat of terrorism or sabotage must also be carefully considered. Nowadays, numerous safety significant events that could occur in different kinds of buildings (skyscrapers, offices, hotels, retail stores, factories, warehouses, sport halls, train and metro stations, churches, road and railway tunnels) are likely to take place: fires, explosions, toxic gas leakages, losses of dangerous goods. Even insignificant incidents can seriously endanger life, assets and natural environment. In particular, fire spreading in large buildings represents a terrifying threat, which can be properly analyzed using computer simulation techniques.

With the continuous advancements of computer technology and the progress made by cellular automata theory, fire spreading models are becoming common engineering tools in the fire safety design and risk assessment of buildings, and can be an efficient approach for fire safety engineering research in buildings and enclosures [1].

Generally, large building fires have a very complicated nature [2]. The mathematical modeling of fire expansion and smoke dispersal inside any sort of large buildings represents a remarkable challenge that has to take into account the system evolution in both time and space. Since the essential physical and chemical processes (convective heat transfer, thermal radiation, combustion chemical reactions, etc.) that govern the fire spreading and smoke expansion interact with each other and with the environment, the computer simulation is not an easy task.

Fire simulation can be applied in specific kinds of analyses, like: a) risk assessment – the simulation results are used for analyzing fire risk of building parts; b) fire safety certification – based on different alternatives provided through computer simulations, fire safety concepts may be studied, developed, or improved in order to comply with fire protection regulations; c) post-fire analysis - when a fire has occurred, computer simulations can be applied to analyze the probable sources of the fire and for identifying the legal responsibilities of involved entities.

This paper propose a cellular automata model for fire expansion based on statistic and probabilistic observations and based on the major air flows directions inside the building.

The rest of the paper is structured as follows. Second section describes our cellular automata model. The third section is meant to depict the transition rules. The fourth section presents a case study. Finally, conclusions are offered.

2 Cellular automata model

The permanent progress in computer technology has inspired simulation tools to become an efficient approach in the comprehension of physical systems. Thus, grid-shaped cellular models, particularly cellular automata (CA), have increased their attractiveness in this sense [3],[4].

A cellular automaton is the simplest model of a spatially distributed system that can be applied to simulate diverse real-world processes due to its capacity to develop complex behaviors. In fact, a cellular automaton is an assembly of cells on a regular grid of specified form that evolves through a number of discrete time steps according to a collection of rules based on the states of adjacent cells. The rules are applied iteratively for as many time steps as desired. Thus, it is feasible to model complex dynamic systems base on specification of the local dynamics of its elements. An additional benefit in using cellular automata (CA) is the support typically offered for displaying the results in a graphical fashion, allowing an easier understanding of the discrete dynamics of the system under investigation.

When utilized as simulation instruments, the CA have revealed to be very practical at the time of developing artificial scenarios, mainly in those domains where other approaches are not suitable.

In order to describe the cellular automaton, which represents the core of our simulation technique, we have to depict its following significant attributes [5]: spatial framework; neighborhood structures; state variables; time; and transition rules.

Spatial framework of cellular automata is represented by a lattice of cells that can be specified in any number of dimensions — typically 2D. This pattern is done usually either using congruent cells (i.e. as a grid of cells), either using other regular shape (e.g. hexagons or triangles). In our case the spatial frameworks is represented by a finite two-dimensional orthogonal grid of square cells.

Neighborhood structures are generally identical limited regions around each cell that provide inputs for the cell in question. In our method, a Moore-shape (Fig.1) of the neighborhood (the cell in questions plus its eight surrounding cells) is used.

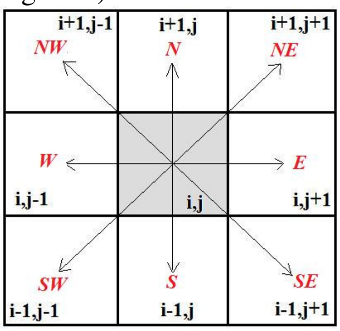

Fig.1: Moore-shape of the neighborhood

State variables of a cellular automaton are represented by the set of attributes that describe its ‘state’ in a particular moment in time. In our case the state of a cell can be 0=EMPTY (describes a cell that is immune to fire: either is already burned, either is impossible to burn – e.g. a concrete wall); 1=UNBURNED (describes a cell that contains materials that can burn but was not yet affected by flames); and 2=BURNING (describes a cell that is burning).

Time is considered as being comprised of discrete steps, when transition rules are applied to obtain the state of every cell included in the grid.

Transition rules establish how the state of a cell varies over time. Based on its own state, its neighbors' states and the transition rules, the cell concludes what its new state should be. All the cells change their states at the same time. In our case we developed complex transition rules that include probabilistic functions and incorporate complex constraints. The transition rules included in our simulation methodology are described in the following section.

3 Transition rules for fire simulation

In our perspective, a burning cell *A(i,j)* contaminates one of its neighbor cells *A(k,l)* because of two components:

- a fixed probability established based on the combustion materials that are placed in the two adjacent cells under investigation. These probabilities are encapsulated in a multidimensional array structure for the entire grid, having three dimensions: two of them (i and j) showing the position in the grid for a precise cell *A(i,j)* and the third showing the position of the neighbor cells).

$$FIXED\_PROB(1:N,1:M,1:8)$$

  where its elements are probabilities:

$$FIXED\_PROB(i,j,k)\in[0,1]$$

  where *N* and *M* are the grid dimensions (our grid has *NxM* cells), and we have eight neighbors that are significant (see Fig.1) – E, W, N, S, NE, NW, SE and SW (we adopted a Moore-shape neighborhood as presented before).
- an evolving probability established at each moment in time based on the fire propagation ellipse model, that relates the probability to spread the fire from *A(i,j)* to an adjacent cell *A(k,l)* with the direction of compound air flow for the cell *A(i,j)*. These probabilities are stored in a three-dimensional array *CHANGING_PROB*, having the same structure as already mentioned *FIXED_PROB*.

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These probabilities are obtained using our novel methodology:

a) We will obtain the velocity of the air flows in each cell of the grid based on a distributed measurement system (e.g. wireless sensor network). In this paper we will consider that these probabilities are constant. Also we consider that the cells that correspond to portions of walls have the velocity of air flow equal to zero.
b) Having the velocity vectors of air flows, we can rely on an ellipse model of fire spreading [6] specified as follows:

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Considering the velocity of air flow for the cell *A(i,j)* being the vector denoted by $\vec{v}(i,j)$, we will draw, for each grid cell, the ellipse using the following general parametric form:

$$\begin{cases} x(t) = x_c + a\cdot\cos t\cdot\cos\varphi - b\cdot\sin t\cdot\sin\varphi \\ y(t) = y_c + a\cdot\cos t\cdot\sin\varphi + b\cdot\sin t\cdot\cos\varphi \end{cases} \quad (1)$$

where the parameter *t* varies from *0* to 2π, the center of the ellipse $(x_c, y_c) = \left(0, \sqrt{a^2 - b^2}\right)$, the major radius $a = k_1 \cdot \|\vec{v}\|$ and the minor radius $b = \frac{k_1}{2}\cdot\|\vec{v}\|$, with k_1 being a chosen constant that reflects the influence of air flows in fire spreading. By this, the origin (center of the cell) is placed in one focus of the ellipse, the ellipse's area grows when the norm $\|\vec{v}\|$ grows and the ellipse is rotated with an angle φ in order to align its major axis with the direction of $\vec{v}$.

c) The probabilities $CHANGING\_PROB(i,j,k)$ are obtained by calculating the length of the segments that start in the center of the cell and end at the intersection of the ellipse with one of the lines having the equations: $x = 0$ for N and S cells, $y = 0$ for E and W cells, $x = y$ for NE and SW cells and $x = -y$ for NW and SE cells.

$$CHANGING\_PROB(i,j,k) = k_2 \cdot \|segment_k\|$$

with k_2 a chosen constant selected to link the segments length with fire spreading probability on that specific direction.

The fire persist in the cell *A(i,j)* a number of time-steps already established and based on the materials present in that cell. This parameter is encapsulated in a matrix:

$$FIRE\_PERSIST(1:N, 1:M)$$

with

$$FIRE\_PERSIST(i,j) \in \mathrm{N}^*$$

Using these variables, the general transition rule for the cell *A(i,j)* at the time-step t, denoted by $A(i,j)_t$ is:

$$A(i,j)_t = \begin{cases} 0 \ if\ \left(A(i,j)_{t-1} = 0\right) or \\ \quad \left(\left(A(i,j)_{t-1} = 2\right) and \left(time\_expired(i,j) = TRUE\right)\right) \\ 1 \ if\ \left(A(i,j)_{t-1} = 1\right) and \left(rand(expression(i,j)_{t-1}) < 0.5\right) \\ 2 \ if \left(\left(A(i,j)_{t-1} = 1\right) and \left(rand(expression(i,j)_{t-1}) < 0.5\right)\right) \\ \quad or\left(\left(A(i,j)_{t-1} = 2\right) and \left(time\_expired(i,j) = FALSE\right)\right) \end{cases} \quad (2)$$

where *time_expired(i,j)* is a counter which is decremented from the maximum value $FIRE\_PERSIST(i,j)$, at every time step when the cell is BURNING, until it reaches 0.

4 Case study

In the following paragraphs we will present how our cellular automata based simulator works. The simulator was developed in Matlab environment.

Fig. 2 describes one level of a large building, where the walls (white lines in the Fig. 2), made of concrete, are considered to be impossible to burn.

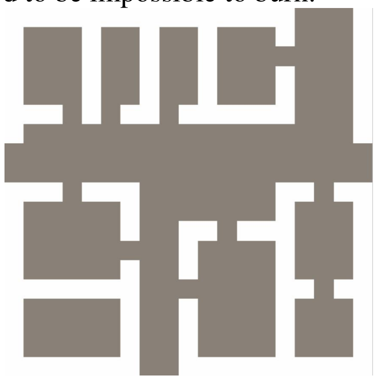

Fig.2: Map of a level in a large building

All the parameters presented before were individualized for each cell. $FIXED\_PROB(i,j,k)$ and $FIRE\_PERSIST(i,j)$ depend on the position of each cell on the grid and the materials that are stored inside the cell. To obtain the $CHANGING\_PROB(i,j,k)$ parameters, we built the map of air flows inside the building (Fig.3), and we drew the corresponding ellipse for each cell of the grid (Fig. 4). This way, we can obtain the intersection of the ellipse with any of the lines having the equations: $x = 0$ for N and S cells, $y = 0$ for E and W cells, $x = y$ for NE and SW cells and $x = -y$ for NW and SE cells. Finally, knowing the length of each segment starting in the center of the cell and finishing in the intersection with the ellipse, we got the $CHANGING\_PROB(i,j,k)$ values.

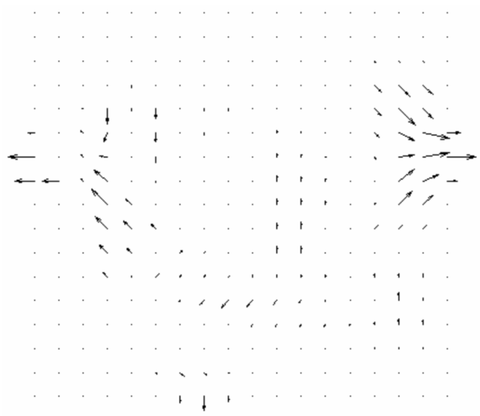

Fig.3: Air flow vectors for each cell of the grid

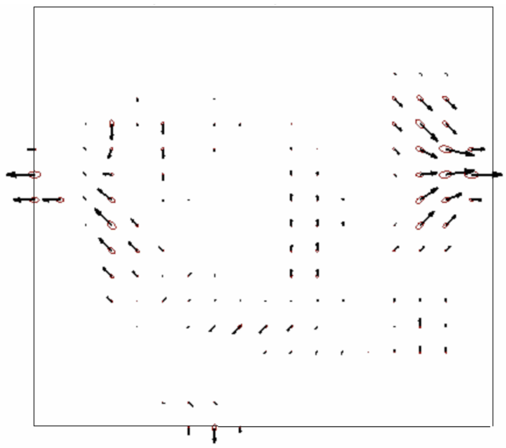

Fig.4: Air flows for each cell with corresponding ellipses

Starting from the map presented in Fig. 2, we considered a fire ignition (marked with black) inside the building (Fig. 5), and the fire spreading develops according to Fig. 6 (ten steps after the ignition) and Fig. 7 (twenty steps after the ignition).

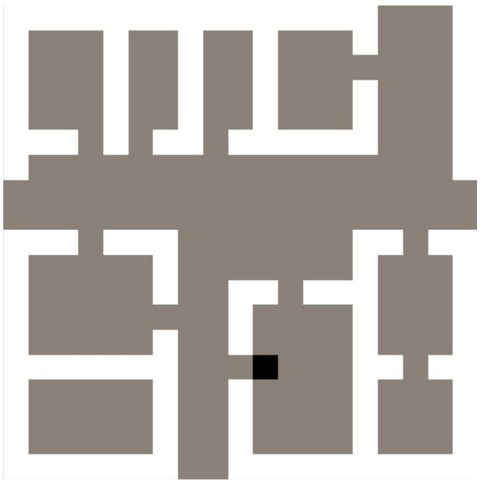

Fig.5. Ignition of the fire in one room (step 0)

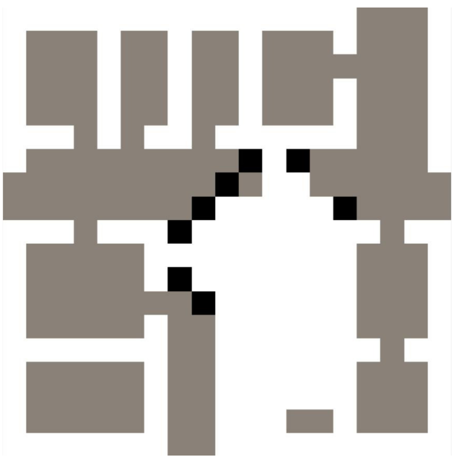

Fig.6: Fire spreading (step 10)

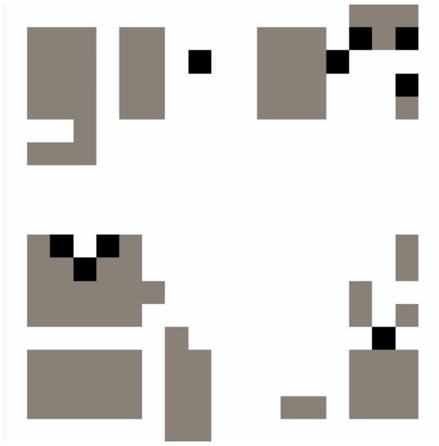

Fig.7: Fire spreading (step 20)

5 Conclusion

This paper presents an efficient fire spreading simulator based on cellular automata for large buildings. Our cellular automata based model for fire expansion relies on statistic and probabilistic observations and is based on the major air flows directions inside the building.

6 Acknowledgement

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