Two-Dimensional Fire Spread Decomposition in Cellular DEVS Models

Lewis Ntaimo
Department of Industrial and Systems Engineering
Texas A&M University
College Station, TX, 77843
ntaimo@tamu.edu

Bithika Khargharia
Department of Electrical and Computer Engineering
The University of Arizona
1230 E. Speedway, Tucson, AZ 85721
bithika_k@ece.arizona.edu

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Abstract

Wildfires and their associated destruction have highlighted the need for real-time simulation systems for accurately predicting fire spread. Such systems would assist fire managers in their efforts to effectively contain potentially catastrophic fires. Modeling and simulation of forest fire spread using the cellular discrete event approach is based on dividing the forest into small areas called cells. Fire spread is then modeled as a contagion process between cells where forward fire spread across each cell is computed using a mathematical fire spread model. Rothermel's mathematical fire spread model allows for computing a one-dimensional maximum forward spread rate and direction. Fire spread in all other directions is *inferred* from this forward spread rate. If this inference is not correctly abstracted it can lead to distortion of fire shapes and incorrect simulation results. This paper proposes a new two-dimensional fire spread decomposition scheme for cellular DEVS models based on Rothermel's mathematical fire spread model. Preliminary simulation results demonstrating the proposed scheme are presented.

1 INTRODUCTION

Ecological problems such as wildfires have highlighted the need for real-time simulation systems for accurately predicting fire spread in order to assist fire managers in fire suppression and containment efforts. Fire spread is a complex propagation process and requires building simulation models that take into account the system evolution in both time and space. Thus fire spread is difficult to accurately model and requires large amounts of data for simulation.

In modeling and simulation of forest fire spread using the cellular discrete event system specification (DEVS) approach [Zeigler et al., 2000; Zeigler and sarjoughian 2002], the forest is divided into small areas called cells. These cells are represented in the computer as a *cell-space*, which preserves their geographical relationships. A mathematical fire spread model is then used to compute fire spread across each cell. Fire spread is simulated as a contagion process between cells. Rothermel's mathematical model [Rothermel 1972] allows for computing a one-dimensional maximum forward spread rate and direction. Fire spread in all other directions is inferred from this forward spread rate, a process we refer to in this paper as *fire spread decomposition.* If this decomposition is not correctly abstracted it can lead to distortion of fire shapes and incorrect simulation results.

Examples of fire spread models that use Rothermel's model include the cellular DEVS models [e.g. Vasconcelos 1993; Vasconcelos, et al., 1995; Ntaimo, et al., 2004], Cell-DEVS [Wainer and Giambiasi 1998] models [Ameghino et al., 2001], discrete time models such as the HFIRE [Morais 2001], and continuous simulation models such as FARSITE [Finney 1998] and BEHAVE [Andrews 1986; Andrews and Chase 1989].

Fire spread decomposition schemes in models based on Rothermel's model [e.g. Andrews 1986; Morais 2001; Ameghino et al., 2001; Ntaimo, et al., 2004] often assume an elliptical fire shape proposed by [Alexander 1985]. The reliance on an assumed elliptical shape is necessary because the present Rothermel's model can only predict a one-dimensional fire spread in the heading portion of a fire. Several works using elliptical fire shapes assume the origin of a fire is at the rear focus of an ellipse [Anderson 1983; Alexander 1985; Andrews 1986], thus providing an implicit means to calculate the backing fire spread rate. Two-dimensional fire spread in all directions is computed from the maximum forward spread rate based on the mathematical properties of the ellipse. Other shapes such as the double ellipse [Anderson 1983], ovoid [Peet 1967] and lemniscate [Brown and Davis 1973] have also been proposed. The double ellipse and the ovoid seek to model varying forward or head fire and backfire spread rates [Green 1983]. It has been observed that although fires may take up the ovoid shape during the initial phase of fire growth, they tend to become nearly elliptical as time passes and increase in size [Green et al., 1983] and/or intensity [Green 1983]. The lemniscate shape is generally assumed to result from fluctuating wind direction or could occur as a natural consequence of high wind speed and very patchy fuels [Green 1983]. The fire shapes would not have to be assumed if the spread rate in all directions could be independently computed from the fuel models, weather, and topography. For example, models based on partial differential equations or PDE's [Muzy et al., 2004] do not require making any fire shape assumption.

The rest of this paper is organized as follows. In the next section we briefly review three basic forest cell fire spread decomposition schemes for cellular fire spread models based on Rothermel's model. In Section 3 we present our new fire spread decomposition scheme and provide some preliminary simulation results to illustrated the proposed scheme in Section 4. We end with some concluding remarks in Section 5 and point out some future work.

2 BASIC FOREST CELL FIRE SPREAD DECOMPOSITION SCHEMES

Modeling fire spread using the elliptical shape for fire-growth often assumes fire to spread in two-dimensions from the ignition point. The fire spread comprises the head fire, flank fire and backfire, as shown in Figure 1. Rothermel's mathematical model computes the maximum head fire spread R and direction θ, which is along the major axis of the ellipse. Let t_i denote the *burn delay*, which is the time it takes for the fire to spread along a distance d_i in direction i. Also, let R_i denote the rate of fire spread in the direction i. Then the burn delay can easily be computed using the following simple equation:

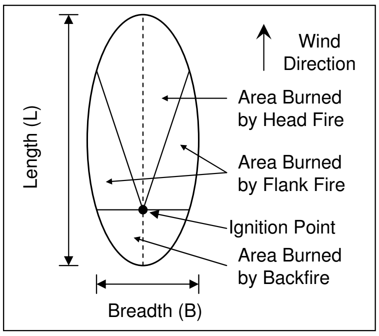

Figure 1: Simple elliptical fire-growth model after [Van Wagner 1969]

$$t_i = \frac{d_i}{R_i} \quad (1)$$

In computing t_i for a given forest cell in cellular discrete event models, it is generally assumed that the fuel and topographic conditions across the cell are uniform, while the weather conditions are allowed to vary. A cell is assumed to ignite based on some probabilistic or deterministic rule. Three basic decomposition schemes for fire spread across a cell can be identified. These are *border-to-border, center-to-center and center-to-border.*

2.1 Cell Border-To-Border Fire Spread

Under the border-to-border decomposition scheme fire is assumed to spread across a cell from border to border. The basic abstraction of fire spread is to consider one burn delay per cell [e.g. Vasconcelos et al., 1993]. In this case the maximum rate of spread computed from Rothermel's mathematical model is used to determine the burn delay along the shortest distance across the cell. After the burn delay elapses, fire spread is assumed to reach the neighbor cells. Obviously this provides a very course approximation of fire spread across a cell. To get better approximations, the maximum rate of spread R and direction θ are used to compute R_i using the elliptical fire-growth model [e.g. Ameghino et al., 2001]. In this case a finite number of azimuth directions are considered, such as $i \in \{0, 45, 90, 135, 180, 225, 270, 315\}$, which correspond to the directions N, NE, E, SE, S, SW, W, and NW. Therefore, a cell that is burning has eight delays computed using equation (1) and scheduled in non-decreasing order. Fire is assumed to spread to the i neighbor when t_i delay elapses. Note that in this approach both head fire and backward fire spread are considered to travel the same distances across the cell. This can result in apparently "thick" fire fronts as a result of longer delays per cell.

2.2 Cell Center-To-Center Fire Spread

A fairly common approach is to consider fire as spreading from the center of the cell to the center of the neighbor cells [e.g. Morais 2001; Ntaimo et al., 2004] as shown in Figure 2. In this case the maximum forward fire spread has to be computed based on the fuel and topographical conditions between the cell centers. Observe that when you consider the cell-space, care must be taken to avoid redundancy as a result of doubly computing burn delays especially for backward fire spread components which may have already been considered when computing the forward spread. This can result in "thick" fire fronts as a result of incorrect longer delays per cell.

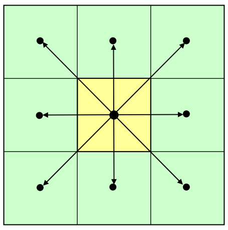

Figure 2: Cell center-to-center fire spread

2.3 Cell Center-To-Border Fire Spread

A variant of the center-to-center decomposition scheme is the center-to-border scheme [e.g. Ntaimo and Zeigler 2004]. In this case fire spread is abstracted as spread from the center of the cell to the border as shown in Figure 3. In the cell-space this can result in faster or "jumpy" fire spread across cells as a result of igniting the cell centers when a spread component reaches the border of the neighbor cell. However, unlike in center-to-center fire spread, computing fire spread across a cell is restricted to the uniform conditions within that cell. Next we propose an alternative cell fire spread decomposition scheme.

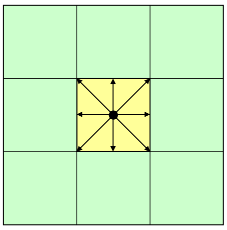

Figure 3: Cell center-to-border fire spread

3 FORWARD CELL BORDER-TO-BORDER FIRE SPREAD

In the new fire spread decomposition scheme fire spread in a cell ignited by fire from a neighbor cell is allowed to spread radially from the point of ignition in the *forward* direction. We refer to this new approach as the *forward cell border-to-border* fire spread to emphasize the fact that fire ignition is assumed to take place at a specific location on the cell border. Initial cell ignition (e.g. from some *igniter* as in [Ntaimo et al., 2004]) is modeled as in the *center-to-border* scheme. Fire spread is assumed to spread radially in the forward direction from the border ignition point towards the neighbor cells. This mimics reality since when fire reaches the cell border it is assumed to have already engulfed the fuels in the cell along its path. Therefore, the *forward* spread comprising the head fire and flank fire spread need to be computed within the ignited cell.

The new decomposition scheme can be described using Figures 4 and 5. In Figure 4 plates *a, b, c* and *d*, respectively, a cell can ignite its *N, S, E*, or *W* neighbor via its corresponding *N, S, E*, or *W* spread component. A cell ignited at the border center (by an incoming *N, S, E*, or *E* spread component) has *seven* spread components. In Figure 5 plate *e* a burning cell can ignite its *N, NE* and *E* neighbor cells via its *NE* spread component; in plate *f* a burning cell can ignite its *E, SE* and *S* neighbor cells via its *SE* spread component; in plate *g* a burning cell can ignite its *W, SW* and *S* neighbor cells via its *SW* spread component; and in plate *h* a burning cell can ignite its *W, NW* and *N* neighbor cells via its *NW* spread component. In this case a cell ignited at the corner has *five* spread components instead of *seven.*

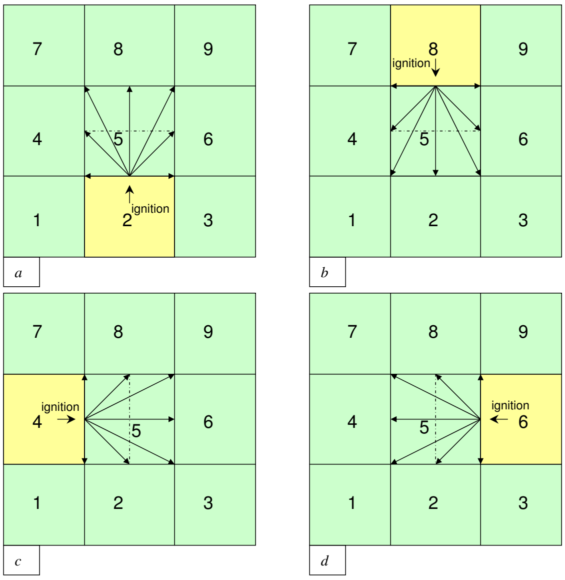

Figure 4: Fire spread components respectively igniting *(a)* N, *(b)* S, *(c)* E and *(d)* W neighbor cells

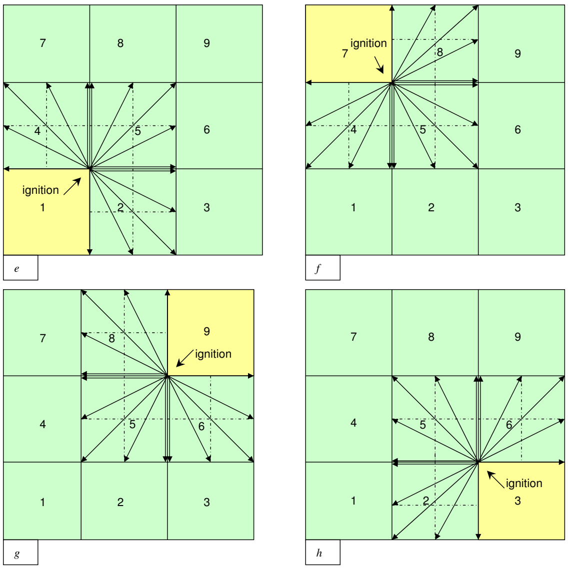

Figure 5: Fire spread components respectively igniting *(e)* NE, *(f)* SE, *(g)* SW and *(h)* NW neighbor cells

The spread components are decomposed so that the head fire and flank fire spread are considered as spreading towards the neighbor cells in the direction of the igniting spread component. The maximum spread component in each cell is computed using Rothermel's mathematical model and decomposed into either *five* or *seven* spread components following the elliptical fire-growth model. The delay for each spread component is then computed using equation 1. One of the advantages of the new decomposition scheme is that unlike in center-to-center or center-to-border decomposition schemes, computing backfire spread when in reality fire is spreading forward is avoided. This closely matches how real fires actually spread. Also, a *NE, SE, SW* or *NW* fire spread component is allowed to potentially ignite the associated three neighbor cells since the spread component is in essence in contact with all three neighbor cells at the corner of the cell. In the other decomposition schemes a spread component is generally allowed to ignite only the cell in its direction. Therefore, this abstraction of fire spread between cells seems more realistic. Finally, in this scheme we have fewer than eight spread components in each cell to consider.

4 EXPERIMENTAL RESULTS

We now report on some preliminary simulation experimental results to demonstrate the proposed cell fire spread decomposition scheme. We compare the results with those obtained using the cell center-to-border decomposition scheme. The experiments were conducted under both uniform and nonuniform wind, fuel and topographical conditions using DEVSJAVA running on a 1.8GHZ 1.0GB PC. A cell-space of size 30 x 30 cells with a cell size of 15 meters x 15 meters was used. The fire in all the experiments starts when the cell with coordinates (14,4) is ignited at the beginning of the simulation.

4.1 Expt 1: Fire Spread Under Uniform Wind, Fuel and Topographical Conditions

In this experiment wind speed was set at 5 kph heading north (N) while the fuel model was set to NFFL-7 (chaparral) for all the cells. A terrain with a slope of 0 degrees was used for all the cells. Figure 6 shows fire evolution for cell center-to-border while Figure 7 shows the results for the forward cell border-to-border decomposition scheme. In each figure the plates from left to right show snapshots of the fire at simulation clock times of about 600, 1200 and 3600 seconds. As can be seen the figures, the fire shapes in both decomposition schemes are similar. However, the forward cell border-to-border results have "thinner" fire-fronts (cells burning). The "thicker" fire-fronts in the center-to-border decomposition scheme can be attributed to the longer delays as a result of computing backward spread within a cell when in fact fire is spreading forward. Also it can be seen in the figures that fire seem to spread faster in the center-to-border scheme as a result of igniting the neighbor cell center when a spread component reaches the border.

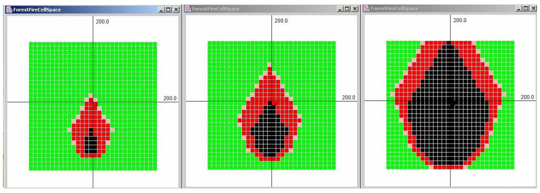

Figure 6: Fire evolution under cell center-to-border

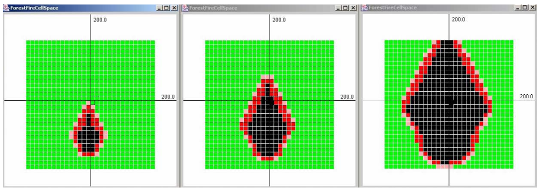

Figure 7: Fire evolution under forward cell border-to-border

4.2 Expt 2: Fire Spread Under Nonuniform Wind Conditions

In this experiment the cell conditions were maintained as in the Expt 1 except for the wind direction. In this case the simulation was initialized with a wind speed of 5 kph heading north (N) and was later changed to head in the north east (NE) direction after about 200 seconds of simulation clock time. The results for the two decomposition schemes are given in Figures 8 and 9. In each figure the plates from left to right show snapshots of the fire at simulation clock times of about 200, 300 and 400 seconds. The results obtained in this experiment are also consistent

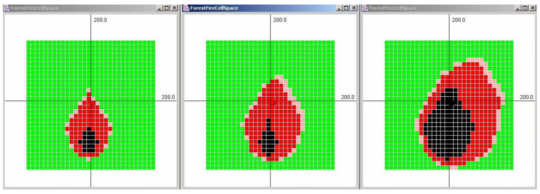

Figure 8: Fire evolution under cell center-to-border

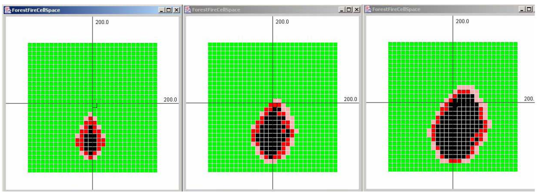

Figure 9: Fire evolution under forward cell border-to-border

with the observations made in Expt 1. Under the center-to-border decomposition scheme the fire fronts are significantly "thicker". In fact, after a change in wind direction, significantly more cells catch fire than shown under the forward cell border-to-border.

4.3 Expt 3: Fire Spread Under Nonuniform Fuel and Topographical Conditions

In this experiment a wind speed of 5 kph heading north (N) was maintained. However the cell-space was set to have three zones from bottom to top each with a different fuel model as in [Ntaimo et al., 2004]. The bottom zone has fuel model NFFL-7 (southern rough) and a terrain with a slope of 15 degrees and aspect 0 degrees, while the middle zone has fuel model NFFL-5 (brush 2 ft) and terrain with a slope of 0 degrees. The upper zone has fuel model NFFL-11 (light logging slash) and a slope of 10 degrees with an aspect of 180 degrees. Figures 10 and 11 show fire evolution results for the two decomposition schemes. As in Expt 1, the plates from left to right in each figure show snapshots of the fire at simulation clock times of about 600, 1200 and 3600 seconds. The results obtained in this experiment are also consistent with the observations made in the previous two experiments.

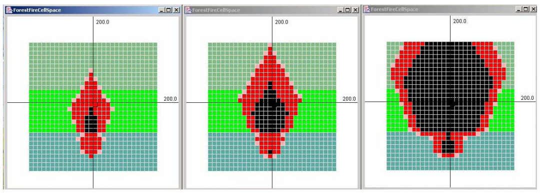

Figure 10: Fire evolution under cell center-to-center

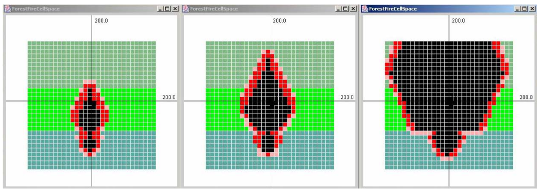

Figure 11: Fire evolution under forward cell border-to-border

5 CONCLUSION

In this paper we propose a new two-dimensional fire spread decomposition scheme for cellular DEVS models based on Rothermel's mathematical fire spread model, which allows for computing a one-dimensional maximum forward spread rate and direction. Fire spread in all other directions is *inferred* from this forward spread rate. The concern is that if this inference is not correctly modeled it can lead to distortion of fire shapes and incorrect simulation results. The preliminary experimental results obtained are promising and demonstrate the viability of the proposed decomposition scheme for fire spread models based on the cellular DEVS approach. Future work include verification and validation of the proposed decomposition scheme.

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