Dynamic Multi-resolution Cellular Space Modeling for Forest Fire Simulation

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ABSTRACT

Multi-resolution modeling is an important research topic in modeling and simulating complex systems. In this paper, the authors develop a multi-resolution discrete event cellular space model with multiple spatial resolution cells, i.e., the spatial sizes of different cells are different. The change of cells' spatial resolutions happens dynamically and adaptively as the simulation proceeds. This work is developed in the context of forest fire simulation. Specifically, as the fire front spreads along the cellular space, cells close to the fire front change to higher resolution (smaller size) and cells far from the fire front change to lower resolution (larger size). The conceptual framework to support multi-resolution forest fire simulation is described. Implementation and preliminary results are presented and discussed.

Keywords: Dynamic multi-resolution, Spatial resolution, Cellular space model, Forest fire simulation, DEVS

1. INTRODUCTION

Multi-resolution modeling is an important research topic in modeling and simulating complex systems. As discussed in [Davis and Hillestad 1993], resolution is a multifaceted concept. A multi-resolution model might mean the model to have multiple temporal resolutions, or multiple spatial resolutions, or multiple levels of abstractions. This paper concerns models with multiple spatial resolutions while their "levels of abstraction" are the same. We develop a cellular space model with multiple spatial resolution cells, i.e., the spatial sizes of different cells are different. The change of cells' spatial resolutions happens dynamically and adaptively as the simulation proceeds. We develop this work in the context of forest fire simulation. Specifically, as the fire front spreads along the cellular space, cells close to the fire front change to higher resolution (smaller spatial size) and cells far from the fire front change to lower resolution (larger spatial size).

Fire spread is a complex natural propagation phenomenon that requires a great deal of computer storage space to accommodate the large-scale spatial and temporal data needed in modeling and simulating it. In cellular space fire spread models [e.g. Vasconcelos 1993; Wainer and Giambiasi 1998; Ameghino et al., 2001; Morais 2001; Ntaimo, et al., 2004] the forest is divided into small areas referred to as forest cells. Fuel and topographical conditions are generally assumed to be uniform across the forest cell. Spatial resolution deals with the resolution in the input spatial data required for fire spread simulation which include fuel type, elevation, slope and aspect. Raster resolutions of 25 to 50 meters are most commonly available for topographic and satellite data and seem to provide acceptable level of detail for heterogeneous landscapes [Finney 1998]. Therefore, forest *cell resolution* (size of the forest cell) affects the accuracy in representing the actual fuel and topographical conditions. Consequently, this *cell resolution* has influence on fire spread simulation results. Note that a high cell resolution, that is, smaller size cells, would represent the actual spatial conditions more accurately. However, dealing with high cell resolutions typically challenges efficient computer simulation. In [Barros and Mendes 1997], a Dynamic Structure Cellular Automata (DSCA) method was developed to represent only the active model cells instead of loading all the cells from the very beginning of a forest fire simulation. This paper takes a different approach where cells are initialized in a low resolution and then change to high resolution when becoming active.

Achieving the "right" spatial resolution has been long research in computer modeling and simulation. Discrete time fire spread simulations such as FARSITE [Finney 1998] dynamically adjusts the simulation time-step to achieve a specified level of spatial detail determined by the *distance resolution*. Also, a process called *rediscretizing* [Richards 1990] is applied to achieve a required level of perimeter resolution, which is the maximum distance allowed between vertices of a polygon [Finney 1998]. The finest resolution used for the simulation must be dependent on the resolution of the spatial data grids used as input [Finney 1998]. Unlike the use of the cellular space approach for large scale high resolution environmental simulation, [Filippi and Bisgambiglia 2002] propose the use of a vector space. In this case a phenomenon is described by its dynamic shape and decomposed in several points that can move using a displacement vector. Each point is allowed to instantiate a new point if there is a change in the space properties or to obtain a better resolution model. Other related work includes Adaptive mesh refinement (AMR) [Berger and Oliger 1984; Berger and Colella, 1989], which refines the temporal and spatial resolutions for regions of the computational domain thus assigning high resolutions for resolving developing features, while leaving less interesting parts of the domain at lower resolutions.

The approach we propose is based on the Discrete Event System Specification (DEVS) formalism [Zeigler et. at., 2000]. As discussed in [Ball et. al., 1996], DEVS-based modeling and simulation provides several advantages for multi-resolution modeling and simulation of ecological systems. With discrete event simulation, a model only performs calculations when it is ready to change states. There is an inherent synchronization in this approach, since models of different resolutions will automatically be staged according to the next event time. The modular construction in DEVS allows each model to be designed for optimum efficiency. As long as the models adhere to certain protocols, they can interact with each other. Furthermore, as will be discussed later, DEVS' variable structure modeling capability allows models at different resolutions to be dynamically added and/or removed during simulation.

The rest of the paper is organized as follows. Section 2 describes several design issues related to the conceptual framework for supporting dynamic multi-resolution cellular space modeling. These design issues include consistency maintenance of cells' state, coupling cells at different resolutions, and resolution change mechanism. Section 3 highlights several implementation issues of multi-resolution cells. Section 4 provides some preliminary results and section 5 concludes this work.

2. CONCEPTUAL FRAMEWORK

Multi-resolution models have been long considered in ecological modeling and simulation. Ideally, each process that we attempt to model should be considered in the context of its own spatial and temporal resolution. This paper focuses on cells' spatial resolution in a cellular space model for forest fire spread simulation. The rationale of this work is to have high spatial resolution cells for "high activity" areas, i.e., the cells around the fire front, and to have low spatial resolution cells for "low activity or zero activity" areas, i.e., the cells far from the fire front. This is because the cells around the fire front are either burning or going to burn soon, thus deserve more computation attentions. The cells far from the fire front are either unburned or already burned out, thus can be treated in low resolution. As the fire front moves during simulation, high resolution and low resolution cells will be dynamically added and removed according to the position of fire front. As a result, this approach enables a high resolution simulation without creating high resolution models (cells) from the very beginning.

As a first step of this work, this paper considers forest cells (in rectangular shape) at two spatial resolutions: a low resolution (with large cell size) and a high resolution (with small cell size). During simulation, a low resolution cell, if necessary, is replaced by four high resolution cells. In the following text, we refer to such a low resolution cell as the *parent cell* and the four new-created high resolution cells as *children cells*. The four children cells, created from the same parent cell, are referred to each other as *brother cells*. The dynamic multi-resolution cellular space model developed in this paper builds from the cellular DEVS model of [Ntaimo et al., 2004]. To set the stage of the conceptual design of this work, next we briefly review the model developed in [Ntaimo et al., 2004].

2.1 A Brief Review of a DEVS Fire Spread Model

The main components of the cellular DEVS fire spread model developed in [Ntaimo et al., 2004] are summarized in Figure 1. In the figure the forest Cell Space is a coupled DEVS model that constitutes the representation of the actual forest in the computer and is divided into forest cells of specified size. The Experimental Frame is composed of the Transducer, Display modules, Forest Cell Igniter, Wind Flow Model, and Fire Fighting Model. The Transducer is used to compute fire spread factors of interest while the Display modules provide visual displays of what is happening in the forest Cell Space. The influence on the forest Cell Space comes from the Forest Igniter, Wind Flow Model and the Fire Fighting Model. The Forest Igniter is used for the initial ignition of selected forest cells while the Wind Flow Model is used to model weather (mainly wind speed and direction). The Fire Fighting Model is used for modeling fire fighting scenarios.

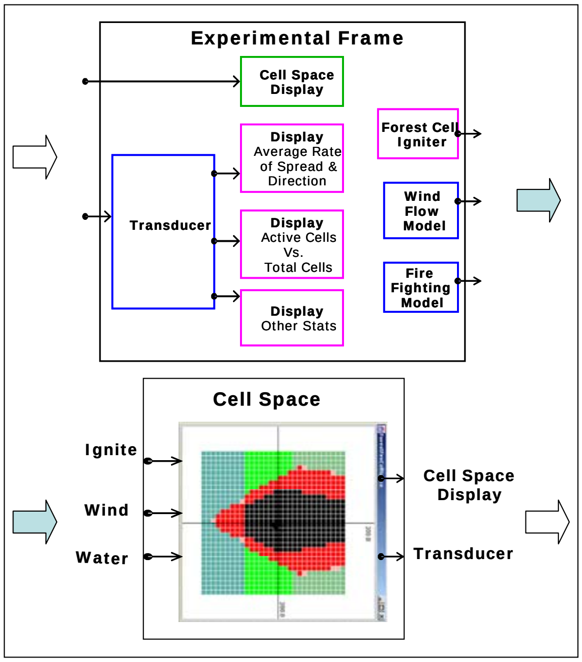


Figure 1. Summary of the cellular DEVS fire spread model after [Ntaimo et al., 2004]

The forest cell is a DEVS atomic model and constitutes the basic building block of the forest Cell Space. Forest cells in the Cell Space are linked together via neighbor-to-neighbor couplings. The forest cell model assumes uniform fuel and topographical conditions, but dynamic weather conditions of the actual forest. Rothermel's mathematical model [Rothermel 1972] is used to compute the maximum forward rate of fire spread and direction in each forest cell. This maximum rate of spread is then decomposed into eight major spread directions (N, NE, E, SE, S, SW, W, NW) using the elliptical fire-growth model of [Alexander 1985]. The dynamics of each forest cell is summarized in Figure 2, which shows the cell state transitions. A formal verification of the forest cell model in Parallel DEVS [Zeigler et al., 2000] is given in [Ntaimo and Zeigler, 2004].

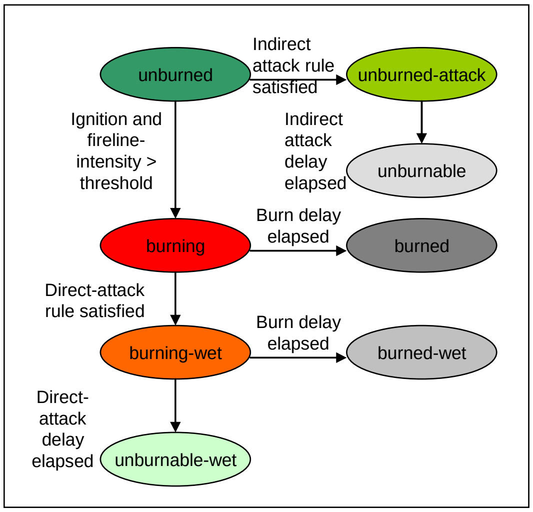


Figure 2. Forest cell atomic model state transitions

2.2 Cell State and Consistency Maintenance

Dynamically replacing a single cell with multiple higher resolution cells (or vice versa) requires a "replacement policy" to ensure consistent transition from the single cell's state to the multiple cells' states. Maintaining such consistency belongs to the consistency maintenance issue as discussed in [Reynolds et. al., 1997; Natrajan 2000]. In [Reynolds et. al., 1997], the authors discuss several types of possible problems related to consistency maintenance, including temporal inconsistency, mapping inconsistency, chain disaggregation, transition latency, thrashing, and network flooding. Avoiding these problems in multi-resolution simulation is important to achieve valid and efficient simulation. In our work, maintaining consistency is facilitated by DEVS models' modular construction. Because of the modular modeling approach, forest cells interact with each other through well-defined input/output ports. This makes it possible for low and high spatial resolution cells to work together, as long as they adhere to the same protocol.

This paper deals with forest cells at different spatial resolutions. Consistency maintenance mainly means to initialize new created cells with the states consistent with the old cells' states at the time of replacement. For example, as shown in Figure 3, when a low resolution cell *C* is replaced by four high resolution cells, *C1*, *C2*, *C3* and *C4*, at time *t*, the four new created cells should be initialized to the states consistent with the old cell's state at time *t*. Similar handling is necessary when the four high resolution cells are replaced by a low resolution cell.

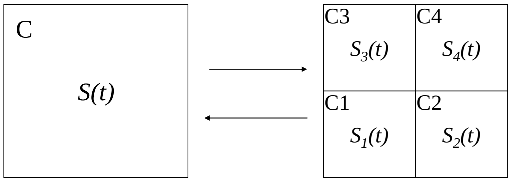


Figure 3: Consistency maintenance of cells' states

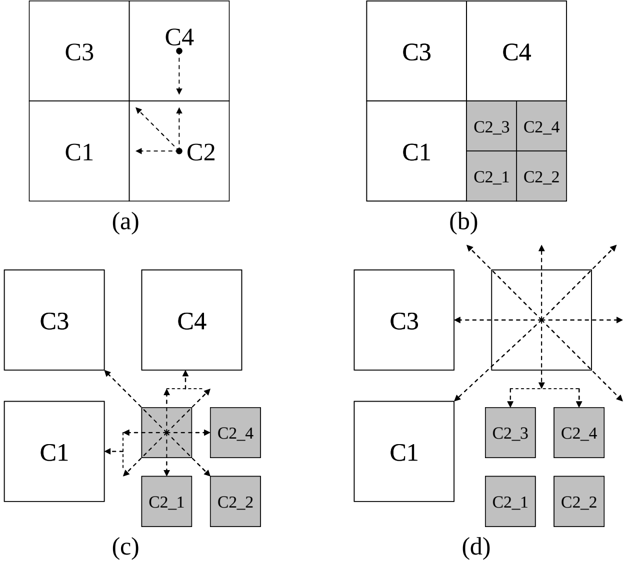
To support consistent transition of cells' states, we identify the main attributes of forest cells into four categories. For each category, below we discuss how to dynamically initiate the state variables to ensure consistent transition of cells' states during resolution change.

- Cells' geometry attributes, including *xCellSize* and *yCellSize*, which represent the *x* and *y* length of the cell. In this paper, a low resolution cell (in rectangular shape) is replaced by four equal-sized high resolution cells (in rectangular shape). Thus when a high resolution cell is created, its *xCellSize* (and *yCellSize*) is half value of the corresponding low resolution cell's *xCellSize* (and *yCellSize*). The opposite is true when a low resolution cell is created.
- Cell's discrete behavioral states such as *unburned*, *burning*, and *burned* (see Figure 2). In general, when a new cell (either high resolution or low resolution) is created, its behavioral state will be initialized to the same behavioral state as that of the old cell(s). For example, when an *unburned* low resolution cell is replaced by four high resolution cells, these high resolution cells are initialized to *unburned* too; when four *burned* high resolution cells are replaced by a low resolution cell, this low resolution cell is initialized to *burned* too.
- Cell's environmental attributes such as fuel type, elevation, slope, aspect, wind direction, and wind speed. Typically, the values of these attributes are obtained from sources outside the simulation model such as GIS databases and weather information centers. Thus when a new cell is created, the values of its environmental attributes can be obtained from those sources with reference of the "current" time. In case the available GIS and/or weather data is not in the same spatial resolution as the spatial size of the cell, aggregation or disaggregation methods should be defined to derive the appropriate information based on the closest spatial data that is available.
- Cell's fire spreading attributes such as fireline intensity, and fire spreading speed and direction. When a cell is burning, the values of these attributes are calculated

from fire spread models, such as Rothermel's semi-empirical model [Rothermel 1972], based on the cell's other attributes mentioned above. In this paper, we define a cell's resolution change to occur only before the cell is burning or after the cell is completely burned out. Thus a cell's fire spreading attributes are not initialized when the cell is created. Instead, they are calculated at runtime after the cell is ignited.

2.3 Coupling Cells at Different Resolutions

A cell interacts with its neighboring cells through couplings between cells' input/output ports. A cell affects its eight neighboring cells through eight output ports: *outN*, *outNE*, *outE*, *outSE*, *outS*, *outSW*, *outW*, and *outNW*, which represent eight fire spreading directions corresponding to azimuth (degrees measured clockwise from the north) of 0, 45, 90, 135, 180, 225, 270, and 315 degrees, respectively. Accordingly, a cell is affected by its eight neighboring cells through eight input ports: *inN*, *inNE*, *inE*, *inSE*, *inS*, *inSW*, *inW*, and *inNW* (see [Ntaimo et al., 2004] for more details). If a cell and its neighboring cells are all in the same resolution (either low resolution or high resolution), couplings between this cell and its neighboring cells can be easily established based on their relative positions. To give an example, Figure 4(a) shows a portion of a cellular space model with four low resolution cells: *C1*, *C2*, *C3*, *C4*, and some outgoing couplings (denoted by dashed arrows) of *C2* and *C4*. Because all the four cells have the same resolution, naturally a cell's output port that represents a particular fire spreading direction is coupled to its neighboring cell along that direction. For example, *C4* is north of *C2*. Thus *C2's* output port *outN* is coupled to *C4's* input port *inS*. Meanwhile, *C4*'s output port *outS* is coupled to *C2*'s input port *inN*. Other couplings between cells can be established in a similar way.



(a) (b)

(c) (d)

Figure 4: Couplings between cells

The situation becomes more complex when cells at different resolutions neighbor each other and work together. Figure 4(b) shows a multi-resolution setup where the low resolution cell *C2* in Figure 4(a) is replaced by four high resolution cells *C2_1*, *C2_2*, *C2_3*, and *C2_4*. In this system, for those neighboring cells that belong to the same resolution, the couplings between them can be established in the same way as described above. However, if two neighboring cells are in different resolutions, their coupling relationship is dependent on not only the relative position of the two cells, but also the source/destination cell's resolution. To illustrate this, Figure 4(c) and Figure 4(d) depict the outgoing couplings of a high resolution cell *C2_3* and a low resolution cell *C4*, respectively, for the model shown in Figure 4(b). In general, if a low resolution cell is north of a high resolution cell, the high resolution cell's both *outN* and *outNE* (or *outNW*, dependent on the location of the high resolution cell) ports will be coupled to the low resolution cell's *inS* port. Meanwhile, the low resolution cell's *outS* will be coupled to both the two high resolution cells' *inN* ports. For example, in Figure 4(c), cell *C2_3*'s *outN* and *outNE* ports are coupled to cell *C4*'s *inS* port (note that, not shown in the figure, *C2_4*'s *outN* and *outNW* ports are also coupled to cell *C4*'s *inS* port); in Figure 4(d), cell *C4*'s *outS* port is coupled to the *inN* ports of both *C2_3* and *C2_4*. Similar rules apply if a low resolution is east (or south, or west) of a high resolution cell. If the low resolution and high resolution cells' relative position is in diagonal direction, e.g., *C3* and *C2_3* in Figure 4(c), their couplings follow the same rules as those for single resolution cells described before.

To enable systematic ways of dynamically adding cells' couplings during simulation, each high resolution cell should know its relative position, *i.e.*, bottom-left, bottom-right, top-left, or top-right, in the space of its parent (low resolution) cell. A labeling schema can be employed to support this. This labeling schema, represented by a cell's ID, should make it easy to determine a cell's resolution as well as its exact position. This capability is important for the Resolution Manager (see section 2.4) to check a cell's neighboring cells and add couplings between them based on their IDs. A realization of such a labeling schema is discussed in Section 3.

2.4 Mechanism of Resolution Change

Having discussed the consistency maintenance of cells' states and the couplings between cells, this section describes the mechanism of resolution change, i.e., when, and how to conduct resolution change. Figure 5 shows the three major components involved in resolution change: a cellular space model with multi-resolution cells, a resolution manager (RM) model responsible for changing resolution, and a CellGridView that displays the cell grid during simulation. Other components such as weather models, experimental frame models, are the same as in [Ntaimo et al., 2004]. They are not involved in resolution change and are not shown in the figure.

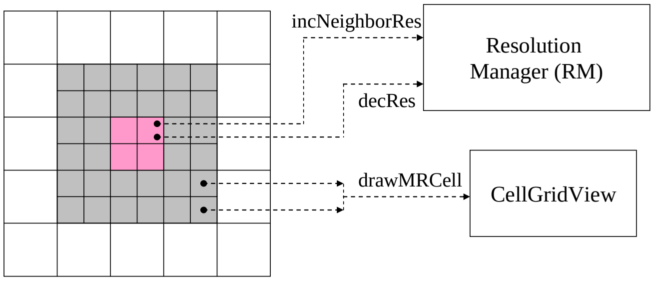


Figure 5: Resolution change mechanism

As mentioned before, the task of resolution change is to dynamically increase resolution for the cells close to the fire front, and to decrease resolution for the cells that are either unburned or already burned out. In this work, unburned cells are initialized to low resolution, thus decreasing resolution mainly means to decrease resolutions for those (high resolution) cells that are burned out. A resolution change is initiated by a cell and carried out by the RM. To increase resolution, a "change ahead" scheme is employed to ensure that cells are already in high resolution before they are ignited. Specifically, whenever a cell starts to burn (transits into the *burning* state), it sends the RM an "*incNeighborRes*" message to request to increase its neighboring cells' resolution. The reason behind this is that a start-to-burn cell will soon ignite its neighboring cells. Thus increasing those neighboring cells' resolutions will guarantee they are in high resolution before the fire front reaches them. The RM will check the corresponding neighboring cells after receiving the "*incNeighborRes*" request and increase their resolutions if needed. To decrease resolution, a cell sends RM a "*decRes*" message to request to decrease its own resolution. After receiving this request, the RM will check the behavioral states of the other three *brother cells*. Only when the four bother cells are all burned out, the RM will decrease their resolution by replacing them with a low resolution cell. Otherwise, the RM ignores the request.

In order to support resolution change described above, each cell is coupled to the RM. Figure 5 shows such couplings (denoted by dashed arrows) for one cell. Figure 5 also shows that after the four cells (in pink color) in the center transit to the *burning* state, the resolutions of their neighboring cells (in grey color) are increased. These high resolution neighboring cells stay in the *unburned* state until they are ignited by the burning cells. At that time, they request the RM to increase their neighboring cells' resolutions. As the simulation proceeds, the change of cells' resolutions happens dynamically along with the spread of the fire front.

Realization of dynamic replacement of multi-resolution cells is supported by DEVS' variable structure modeling capability. Variable structure modeling allows DEVS models and their couplings to be dynamically added and/or removed during simulation (for example, see [Barros, 1996; Uhrmacher, 2001; Pawletta and Lampe, 2002]). Using the structure change operations developed in the DEVSJAVA environment [Hu, et al., 2005], replacing a cell with multiple higher resolution cells can be accomplished by the following four-step operations: *Create new cells*, *Add the new cells*, *Remove the old cell*, *Add couplings between the new cells and other cells*. With this capability, the pseudo code of RM for increasing resolution and decreasing resolution, respectively, is given below. In the code, *absorbing states* mean the behavioral states that will stay there forever, such as *unburnable*, *burned* as shown in Figure 2.

Pseudo code for decreasing resolution:

```
increaseNeighborResolution ( myCell_ID ) {
  getNeighborCells ( myCell_ID );
  for ( each neighboring cell){
     if ( the cell is in low resolution ) {
        if ( the cell is not in absorbing states ){
           create and initialize four new children cells;
           add the four children cells;
           remove the parent cell;
           add couplings between cells and their neighbors;
           add couplings with other models
                                  such as RM, CellGridView;
        }
     }
  }
}
```

Pseudo code for decreasing resolution

```
decreaseResolution ( myCell_ID ) {
   get the other three brother cells ( myCell_ID );
   if ( all four cells are in the same absorbing state ){
      create a low resolution cell;
      initialize the cell to the current state;
      add the cell;
      remove the four high resolution cells;
      add couplings between the cell and its neighbors;
      add couplings with other models
                                such as RM, CellGridView;
   }
}
```

Another component shown in Figure 5 is the CellGridView, which is responsible for displaying the multi-resolution cellular space as well as the progress of fire spreading. The CellGridView is designed to be able to display cells with multiple spatial sizes. Meanwhile, it reflects cells' resolution change in real time as multi-resolution cells are added and/or removed dynamically. To support the display, each cell is coupled to the CellGridView. Figure 5 shows such couplings for two cells.

3. IMPLEMENTATION ISSUES

Built from the fire spread and suppression DEVS model developed in [Ntaimo et al., 2004], several changes have been made in order to support multiple resolution models to work together. The major changes include supporting dynamical replacement of different resolution models and the capability to display multiple resolution cells.

In our implementation, each cell, either in high resolution or in low resolution, has a unique ID *(xcoord, ycoord, resolutionIndex)*, where *xcoord* and *ycoord* represent the cell's position in the two dimension cell space and the *resolutionIndex* stands for the index of the cell's resolution. A labeling schema is realized in order to easily determine a cell's resolution and its exact position. This labeling schema assigns *resolutionIndex* (an integer number) with different values based on a cell's resolution and its relative position. Specifically, *resolutionIndex* being 0 refers to a low resolution cell. Its value being 1 to 4 refers to the four high resolution cells, among which 1 for the bottom-left cell, 2 for the bottom-right cell, 3 for the top-left cell, and 4 for the top-right cell. With this approach, a cell's resolution and position, and thus its neighboring cells' resolutions and positions, in the cell space can be determined. A similar labeling schema is employed in CellGridView, which displays multi-resolution cells during simulation.

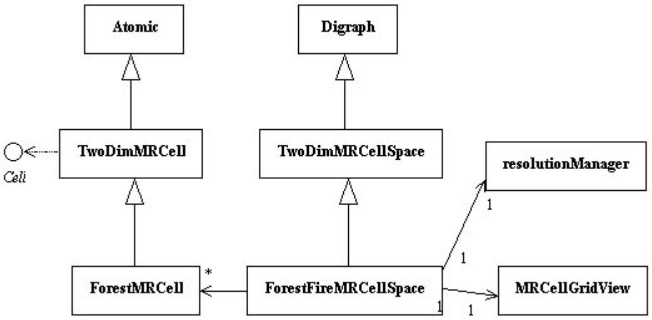
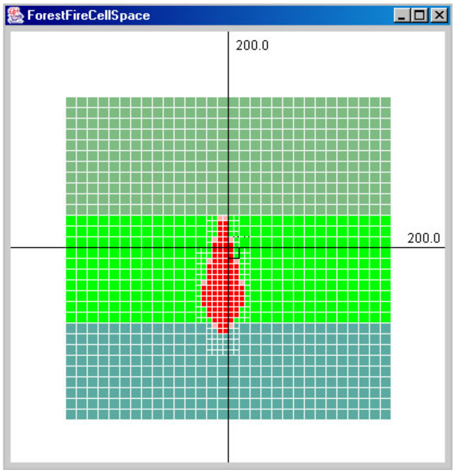


Figure 6: Main classes for multi-resolution modeling

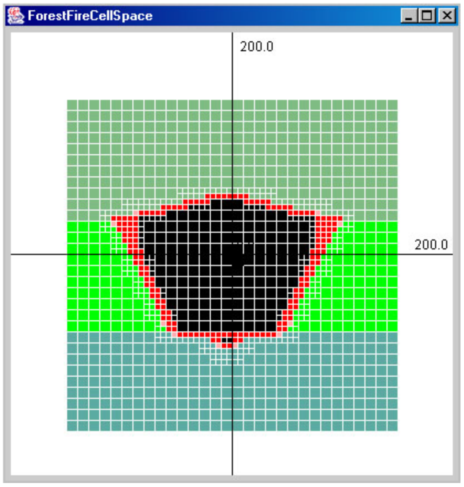
Class diagram for the main classes involved in multi-resolution modeling and simulation is shown in Figure 6. These classes are extended from their corresponding classes developed in [Ntaimo et al., 2004] to support cells with multiple resolutions. For example, the *TwoDimMRCell* class has a new attribute *resolutionIndex* as part of its ID; the *TwoDimMRCellSpace* class has new operations to support couplings between cells at different resolutions.

4. EXPERIMENT RESULTS

Preliminary results were obtained using the developed dynamic multi-resolution modeling and simulation. Figure 7 shows two snapshots of a simulation to illustrate how cells' resolutions are increased and decreased as the fire front moves. The simulation starts with 30 x 30 cells all in low resolution. Fire spread starts when the cell (14, 8) is ignited. The wind direction is from south to north with speed 5 kph. Each cell has size 15.0 x 15.0 meters. Cells are initialized with different fuels and slopes as represented by different colors. Figure 7(a) shows that the neighboring *unburned* cells surrounding the *burning* cells (in red color) increase their resolutions from low to high. The cells far from the fire front still maintain their low resolution. Figure 7(b) shows that as the fire front moves, the cells surrounding the fire front dynamically increase their resolutions. Meanwhile, the cells that are already burned out (in black color) decrease their resolutions by replacing four high resolution cells with one low resolution cell.



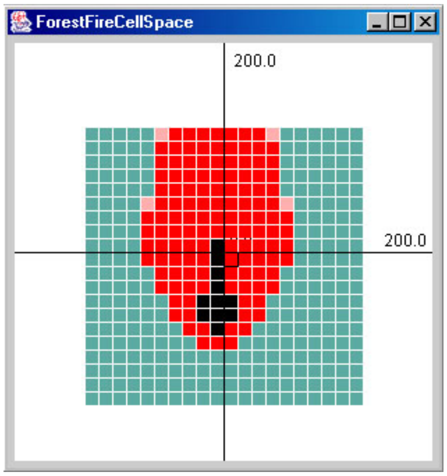
(a) Simulation snapshot 1



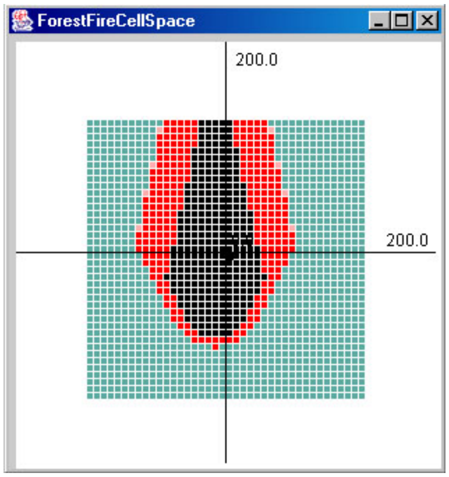
(b) Simulation snapshot 2

Figure 7: Dynamic multi-resolution simulation

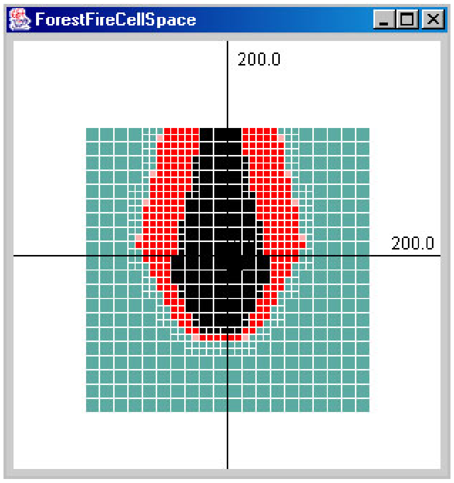
In order to quantitatively demonstrate the developed multi-resolution simulation, we compare the preliminary results of three simulations by varying cells' resolutions while maintaining all other conditions the same. They are: simulation using all low resolution cells (Figure 7(a)), simulation using all high resolution cells (Figure 7(b)), and simulation using dynamic resolution cells (Figure 7(c)). In all three simulations, we consider 20 x 20 cells with size 15.0 x 15.0 meters (40 x 40 cells with size 7.5 x 7.5 meters for the simulation using all high resolution cells). The wind direction is from south to north with speed 5 kph. All cells have the same fuel model and slope. All three experiments are run with the same amount of simulation time.



(a) Simulation using all low resolution cells



(b) Simulation using all high resolution cells



(c) Simulation using dynamic resolution cells

Figure 8: Three simulations using different resolution cells

Figure 8 shows that the simulation result obtained using the dynamic resolution approach are (almost) the same as that obtained from using all high resolution cells. This is expected because in dynamic resolution approach, a low resolution cell will always increase its resolution before it is ignited. Thus the dynamic resolution approach should have the same effect as that in using all high resolution cells. Figure 8 also shows in the simulation using all low resolution cells, the total amount of area (represented by red and back cells) affected by the fire is (almost) the same as those from the other two approaches. However, it can be seen that the "*burned out*" speed in the low resolution simulation is slower than that observed in the other two simulations – as indicated by the total number cells burned out. We think this can be attributed to the way that a cell's fire spreading is modeled using the center-to-center spread approach. More research [see e.g. Khargharia and Ntaimo, 2006] is on the way to experiment using different spread decomposition schemes.

5. CONCLUSIONS

This paper presents a dynamic multi-resolution cellular space model for forest fire simulation. Using dynamic multi-resolution simulation, as the fire front spreads along the cellular space, cells close to the fire front change to higher resolution (smaller spatial size) and cells far from the fire front change to lower resolution (larger spatial size) dynamically. The conceptual framework of this work is described and some experiment results are presented. Preliminary results show that the developed dynamic multi-resolution simulation enables a high resolution simulation without creating high resolution models (cells) in the first place. The correctness of this approach is supported by the "change ahead" scheme in the mechanism of resolution change, which guarantees that a cell is in high resolution before it is ignited. Because of this, the fire ignition process among cells actually works the same way as that in using all high resolution cells.

Although this paper considers cells at only two spatial resolutions, more resolutions can be supported by extending this work. Furthermore, similar approaches can be developed and applied to other ecological or physical diffusion phenomena. Future work of this research includes developing methods to handle different raster resolutions of GIS data, applying this to larger scale problems, and developing algorithms to support efficient simulation of large scale models.

6. ACKNOWLEDGEMENT

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